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# DIELECTRIC PHENOMENA

## *II.—Electrical Discharges in Liquids*

# DIELECTRIC PHENOMENA

## II.—Electrical Discharges in Liquids

*by S. Whitehead, M.A.*

*Edited*
*with a Preface*
*by E. B. Wedmore*
*M.I.E.E., F.Inst.P.*

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# PREFACE

This volume is the second in a series being prepared by the Electrical Research Association, giving a critical résumé of available information on the subject of dielectric phenomena, with particular attention to the theoretical basis, and particular reference to the failure of insulation in service. The importance of the subject in the field of electrical engineering need not be stressed.

The present volume deals with discharge phenomena in liquids. The matter is somewhat differently arranged from the plan employed in the first volume, differences in the matter to be presented requiring this. The experimental evidence and empirical data have been given first, followed by a critical résumé of the theories which have been put forward, which are considered in the light of the facts detailed in the earlier part of the volume.

References will be found in various parts of the volume to work done for the Electrical Research Association. That Association desires to put on record its appreciation of the work carried out on its behalf by several investigators, particularly Mr J. T. Cogle at the Metropolitan-Vickers Research Laboratories, and Mr A. N. Jackson at University College, London, for extensive investigations into insulating oils, and Mr R. W. Plumbly at the City and Guilds Technical College, South Kensington, for investigation of the phenomenon of corona in oil.

A bibliography is appended, but its preparation has presented some difficulty, as some of the work criticised has not yet been published independently. New matter will be found in several parts of the work.

E. B. WEDMORE.

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# INTRODUCTION

When a difference of potential is applied to a pair of electrodes immersed in a liquid, a small conduction current at first passes. If the voltage is raised sufficiently, an unstable rise in the current takes places at a certain voltage which may discharge the circuit, or may result in the formation of an arc if the available power be adequate. In practice the sudden rise of current generally opens the circuit automatically. This instability of current is accompanied by a flash, with some amount of decomposition of the liquid, and the production of gas. The phenomenon is analogous to sparkover in gases, and is therefore termed here *sparkover in liquids*.

Previous to the occurrence of sparkover, transient flashes may pass between the electrodes or, if the latter are widely spaced, streamers may spread out into the gap. The former are known as *pilot or preliminary sparks*, and the latter as *high voltage streamers*. In a few cases a glow may be observed previous to sparkover, somewhat similar to corona in air, but generally much more unsteady and partaking rather of the nature of small brushes than of a glow. This has been called *corona in liquids*. These phenomena resemble sparkover in that there is a measure of instability in the passage of electricity across the gap, but it is not progressive and an arc is not formed.

The effects generally, including sparkover, are known as *discharges in liquids*. Sparkover is also termed the *breakdown* of the liquid, since the insulating properties of the medium are completely lost, at least temporarily.

The voltage at which sparkover occurs is known as the *sparkover* or *breakdown voltage* (*B.D.V.*). Similarly, in the case of corona, we speak of the *corona voltage*. The term *critical voltage* is used generally to denote a voltage at which discharge effects take place.

In the case of gases (see *Electrical Discharges in Gases*), the discharge phenomena could be treated in a more or less systematic fashion from the standpoint of ionisation by collision. Our knowledge in the case of liquids is too limited for this. Accordingly, an account of the experimentally observed effects of different variables upon discharges in liquids, particularly with reference to critical voltages, is first given. Corona and preliminary sparking are treated last, as their relations with other phenomena are not very well known and they have not so far been considered as of very great importance. The investigations considered below apply, as a general rule, to alternating fields, since high alternating voltages are more frequently met with than high direct current stresses. Finally, a short account is given of the theories of the mechanism of discharges in liquids in the light of the experimental evidence previously described.

Since the breakdown strength of a liquid depends, in many cases, more upon the nature of the impurities which it contains than upon the nature of the liquid itself, the first chapter is devoted to the study of the general nature of these impurities and of their effect upon the breakdown strength. It is important that a distinction should be made between the breakdown of a pure and an impure liquid. To a large extent the theories put forward to explain variations of the B.D.V. with different variables have actually been theories of the behaviour of the impurities under these conditions. The value of such theories cannot be very easily assessed, nor, in fact, can the significance of experimental work in general be appreciated without a knowledge of the general effect of small quantities of the foreign substances likely to be present.

# CHAPTER I

## EFFECT OF IMPURITIES

### (*a*) INTRODUCTORY

IN this section the general nature of the impurities to be found in liquid dielectrics will be examined, and consideration will be given to the relative magnitude of their effects upon the electric strength. The characteristic effects of impurities under particular conditions will be described in the sections dealing with the effect of those conditions.

An initial difficulty must first be mentioned here, although it will be considered in more detail subsequently. Measurements of breakdown strength with liquids show great variations between observations taken under apparently the same conditions. According to Hayden and Eddy,[1] these variations follow more or less a probability law (although not sufficiently closely to be adequately represented by one), thus indicating an inherent lack of homogeneity in the material. If this were universally true then, from the point of view of electric strength, we could not speak of a pure liquid, since any liquid must show essential variations in quality. However, throughout the present report it is assumed that a pure liquid is homogeneous, and that there is a B.D.V. characteristic of it under given external conditions. The main ground for this assumption is that the probability of a perceptible variation in structure is small on any kinetic theory. In general, it is to be expected that variations due to the presence of foreign substances will account for the greater part of the divergences observed.

### (*b*) SOLID IMPURITIES

### (i) *Soluble Impurities*

The only liquid dielectrics which have been extensively studied are insulating oils, and even these have not been examined very closely from the point of view of the effect of dissolved solids upon the electric strength. Insulating oils dissolve comparatively few solids, and these are largely of a nature similar to the solvents. Oil will, for example, dissolve paraffin wax, rubber (particularly when hot), and certain varnishes if the latter have been made from substances of similar chemical composition. It certainly also dissolves traces of electrolytic impurities.

---

[1] Hayden and Eddy, *A.I.E.E.* (July and February 1922).

We may divide the dissolved solids into two main classes—those which are effectively undissociated in solution, and those which are dissociated to some extent. In regard to the former class we cannot speak with certainty of their effect upon the B.D.V. Armstrong[1] has found that rubber in contact with transformer oil lowers its B.D.V. considerably. This may not be the effect of any solution of the rubber, as it is not known whether it was clean. An oil may be so badly contaminated that it is quite opaque. Although in such a case we should expect a fair amount of dissolved solids, yet the B.D.V. may not actually be lowered to any great extent. On the other hand, dissolved solids may affect the B.D.V. by raising the viscosity and by making the oil more hygroscopic. Paraffin wax, varnishes, and, of course, rubber would increase the viscosity, which would probably have the effect of lowering the B.D.V. of contaminated oil owing to the greater stability of fibrous and liquid bridges. On the other hand, in the absence of bridge-forming impurities, the B.D.V. of the solution would probably be higher than that of the original pure oil. There is some ground for attaching importance to the question of viscosity on account of the effect of temperature. This will be discussed in Chapter III. If, again, the oil becomes more hygroscopic, the B.D.V. will be lowered ; since the presence of moisture certainly lowers enormously the B.D.V. of oil in which fibres, etc. are present, whereas the effect of pure water alone is not excessive though appreciable (*vide infra*).

Apart from these indirect effects it is difficult to assess the importance of the dissolved solids considered. The effect probably varies largely with different materials, and so far the matter has not been examined with sufficient care to enable definite statements to be made.

---

[1] Armstrong, *Electrical World* (27th December 1913).

There is a fair amount of evidence that electrolytic impurities exist in all liquid dielectrics. The phenomena of conductivity, with its positive temperature coefficient, and the anomalous irreversible charging current [1] are most simply explained on the assumption of the presence of ions. It is not certain, however, whether the electrolytes (if solid) are dissolved in the liquid itself or are dissolved in the impurities in the liquid. Such dissolved electrolytes should have a marked lowering effect on the B.D.V. If we adopt the hypothesis of ionisation by collision, as do Gunther Schultze [2] and Draeger,[3] then the more ions present the lower the B.D.V.: since in the case of liquids the low ionic mobilities would require a large volume of initial ionisation to make the discharge possible. Of course, from conductivity experiments we know there are more ions present in oil than in air. On a pyro-electric theory the B.D.V should also be lowered, since the greater the number of ions the more energy is supplied to the dielectric and the lower is the B.D.V. Shrader [4] considers, without making specific assumptions as to the mechanism, that the D.C. conductivity gives a valuable guide to the breakdown properties of a liquid, and he is representative of a large body of opinion.[5] The available evidence, however, is inadequate.

Most of the above considerations are likely to apply to other liquid insulators, although few of these have been tested. It would be interesting to do so, since substances such as benzene are very good solvents, and the effects we are looking for would be available in an enhanced form. Alcohol would also be a good material for experiment with electrolytes, since, although alcohol is itself negligibly dissociated, dissociation of solutes takes place therein. Its electric strength is, however, very low owing to the presence of the hydroxyl group.

---

[1] Hartshorn, "Critical Résumé of Recent Work on Dielectrics," *J.I.E.E.* (November 1926).

[2] Gunther Schultze, *Zeitschrift für Instrumentenkunde* (March 1923); and *Jahrbuch der Radio und Elektronik*, **19**, 92, 1922.

[3] Draeger, *Archiv für Elektrotechnik*, **12** (August 1924).

[4] Shrader, *G.E.C. Review* (November 1925).

[5] In this connection, Steinmetz, *Trans. A.I.E.E.* (1893), **10**, should be consulted.

With regard to liquids other than oils, it can only be said that their electric strength appears to be lowered by all kinds of dissolved impurities. There is not sufficient evidence to say which kinds of impurities are most important. In the case of electrolytes dissolved in a liquid such as alcohol, the joulian heat is generally sufficient in practice to overheat the liquid and so destroy its properties; but there is no reason to believe that this applies to the electrically stronger liquid dielectrics.

### (ii) *Insoluble Solids*

Insoluble solid particles may exist in a liquid either as fibres and dispersed particles of microscopic size, or as a colloidal suspension of sub-microscopic particles. The distinction between the two classes cannot, however, be accurately drawn.

#### 1. EFFECT OF RELATIVELY LARGE PARTICLES

The effect of relatively large particles is considered to be of very great importance, and has been examined in some detail. We may regard these particles as small bodies having a specific inductive capacity[1] different from that of the liquid. They need not necessarily be of insulating material, since for the present purposes we may look upon semi-conducting bodies as insulators of high specific inductive capacity. In general, the particles will have a higher specific inductive capacity than the liquid, and accordingly will experience a force given by the scalar product

$$v(\epsilon-\epsilon')\mathrm{E.DE} \quad . \quad . \quad . \quad . \quad a1$$

where $v$=volume of a particle, $\epsilon$=S.I.C. of particle, $\epsilon'$=S.I.C. of liquid, E=field, and D=operator giving the gradient.

If $\epsilon$ is greater than $\epsilon'$, as is usually the case, the force will urge the particle to the strongest parts of the field, the effect being greater the less uniform the field.

In the case of an arrangement giving a uniform field, such as the field between flared discs or spheres at small spacings, the field is strongest where it is uniform. Here also E is at right angles to DE, so that the particle is in equilibrium. Accordingly the particles will collect in the uniform part of the field and may form a bridge from electrode to electrode. In a non-uniform field, *e.g.* between needle points, the strongest parts of the field are close to the points. The particles will collect there, and bridges will be relatively unstable. The collection of these particles of higher specific inductive capacity will also cause flux concentrations at their surfaces. These flux concentrations will attract other particles, and in this manner stable chains may be formed, even in a non-uniform field. We may now observe that conducting particles may act in a rather different manner. They may be initially attracted to an electrode, and, on touching it, may acquire a charge of the same sign, being subsequently repelled. In this way, if conducting particles are present, a circulating stream may be set up.

---

[1] The term "specific inductivity" is entering into use for this much-discussed quantity. It is analogous to "specific resistivity," "specific conductivity," etc.

The above considerations are borne out by experiment. In many cases it can be seen with the naked eye that fibres are drawn to the strongest parts of the field. Friese [1] has observed microscopically the formation of chains by small carbon and other particles. Schroter [2] and Spath [3] have also observed the effects with a microscope, and Oelschlager [4] has observed the circulation of particles from electrode to electrode. Although it is generally agreed that the presence of these particles lowers the breakdown voltage, opinion is not unanimous as to the importance of particles *per se*, many workers thinking that some other factor must be present. Hirobe [5] says that fibres, etc. are the most important cause of lowered breakdown strength. The particles bridge the gap, and breakdown takes place along the bridge. In support of this he quoted experiments showing that if the electrodes are cleaned with materials liable to leave adhering fibres, the B.D.V. is very much decreased whether the liquid (oil) is dry or not. Wet oil does not show a very much lowered B.D.V. unless these fibres are present. Water and fibres in conjunction

[1] Friese, *Siemens Science Journal* (March 1922).

[2] Schroter, *Archiv für Elektrotechnik* (March 1923).

[3] Spath, *Archiv für Elektrotechnik* (30th June 1923).

[4] Oelschlager, *Siemens Zeitschrift* (January 1925).

[5] Hirobe, Report 25, section iii, Electrotechnical Laboratory, Tokio.

give the lowest figures (see fig. 1). McLaughlin [1] found that in liquids containing large particles, but otherwise pure, very large increases in the conductivity occurred occasionally. These increases are easily explicable upon the fibre-bridge theory, which is supported by microscopic examinations. Stern [2] agrees as to the essential importance of bridges, as do also Hayden and Steinmetz.[3] Friese's [4] work on the formation of carbon chains

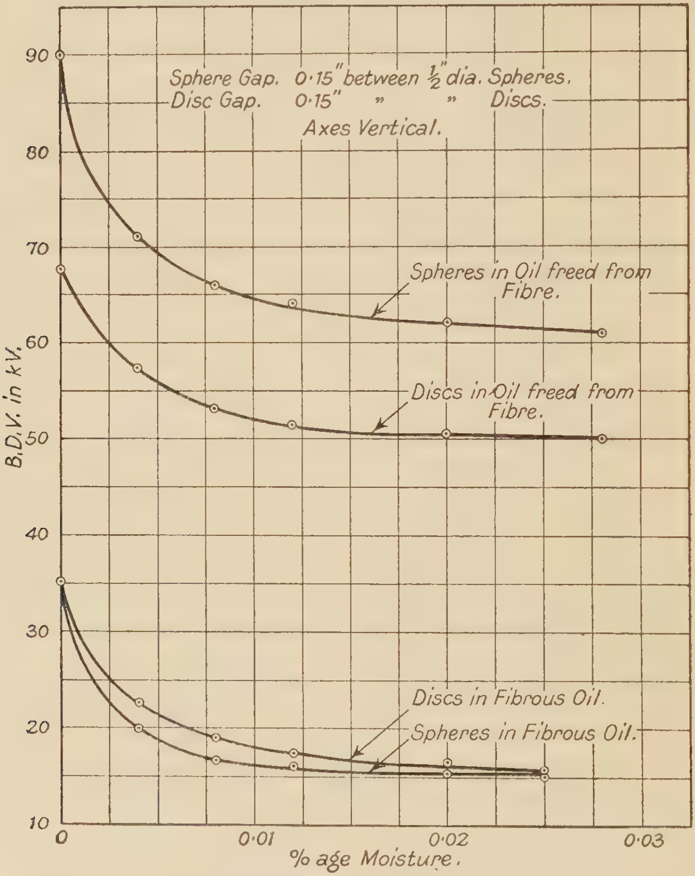

Fig. 1.—Effect of Moisture and Fibre according to Hirobe.

---

[1] McLaughlin, *Electrician* (18th March 1921).

[2] Stern, *E.T.Z.* (30th March 1922).

[3] Hayden and Steinmetz, *A.I.E.E.* (January 1924).

[4] Friese, *Siemens Science Journal* (March 1922).

has already been mentioned. Flight,[1] in a review of the subject, mentions that sediment and free carbon, if in sufficient quantity, have the same effect. On the other hand, there is strong evidence that fibres do not themselves produce a very considerable effect unless moisture is present.

According to Schroter,[2] solid bridges have no effect unless the liquid insulator contains moisture: only a pilot spark is produced in the dry liquid, since the discharge avoids the fibrous particles owing to the flux concentration in the neighbourhood. Draeger [3] also thinks that such solid impurities have a relatively unimportant intrinsic effect.

Extensive tests have been carried out for the Electrical Research Association on this subject. It was found that cotton fibres alone and pressboard fibres alone had not a very great effect upon the B.D.V. of dry oil: the former did not produce more than 30 per cent. drop in the B.D.V. for any of the oils tested, while the latter gave a decrease of about 20 per cent. When, however, the fibres were added to oil containing moisture the B.D.V. was decreased by about 90 per cent. These effects are illustrated in figs. 2 and 3. Most of the decrease in the B.D.V. is caused by the first 20 or 30 mg. of fibre per 10,000 c.c. of oil, subsequent additions producing relatively little effect. From these results it seems clear that a certain percentage of moisture is necessary before the worst effect of the fibres is developed.[4]

The phenomena with carbon were different. A comparatively small decrease in B.D.V. was produced either in dry or in moist oil, but whereas a saturation effect was shown by the dry oil, the decrease of B.D.V. was progressive though small in the moist oil, the B.D.V. falling steadily with further addition of carbon (see fig. 4). It may here be mentioned that Friese [5] found that the carbon which was formed on breakdown lowered the strength of the liquid he used, which was oil of extremely high purity. The initial B.D.V. of this oil was exceptionally high, and the B.D.V.

[1] Flight, *B.E.A.M.A. Journal* (February–March 1921).

[2] Schroter, *Archiv für Elektrotechnik* (March 1923).

[3] Draeger, *Archiv für Elektrotechnik*, **12** (August 1924).

[4] These figures refer only to the conditions employed (see figs. 2 and 3).

[5] Friese, *Siemens Science Journal* (March 1922).

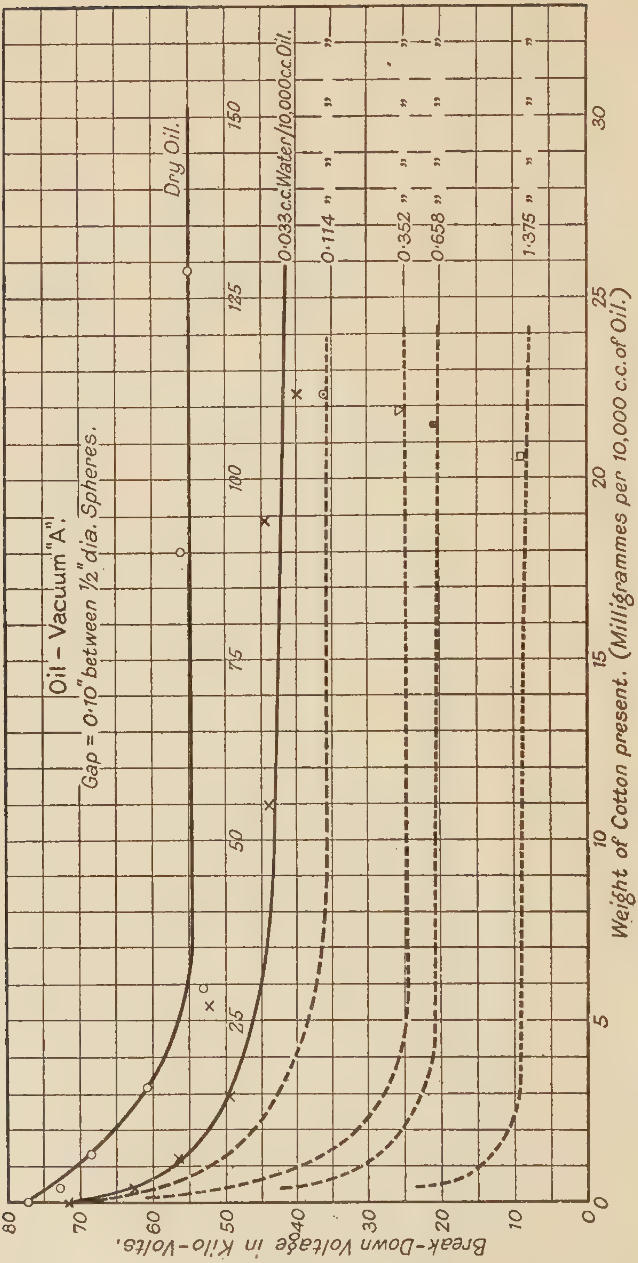

FIG. 2.—The Effect of Cotton Fibres on the B.D.V. of Insulating Oil.

after the formation of the carbon (which must have been dry) was still high enough to be that of a good oil. It is probable that all impurities have a greater effect with liquids of a very high degree of purity. In general we may say that carbon suspensions have a very much less deleterious effect than fibres.

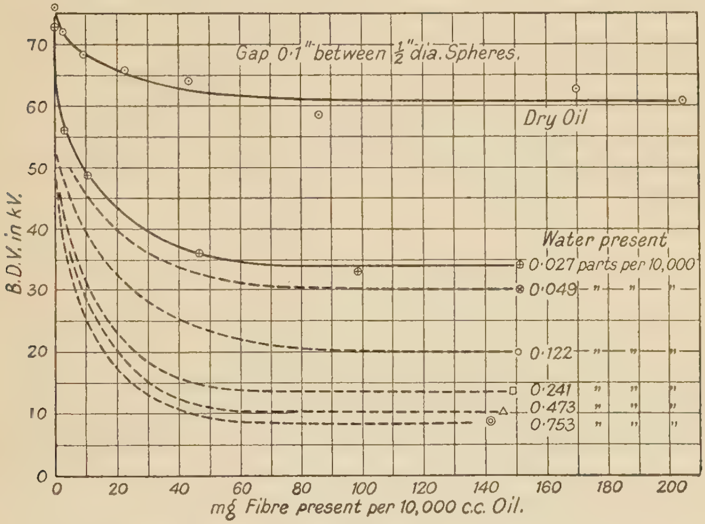

FIG. 3.—Effect of adding Pressboard Fibre to Oil (Vacuum F.F.V.).

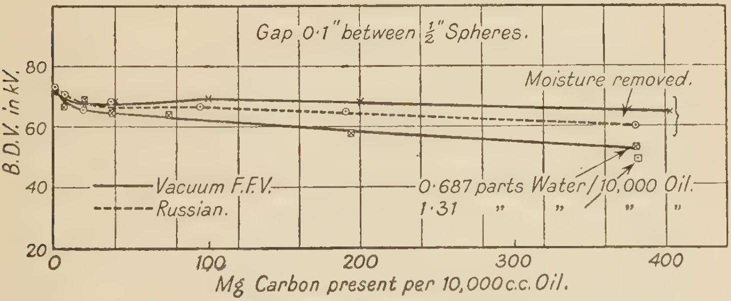

FIG. 4.—Effect of Carbon on Oil.

Some of the variations that appear in the opinions and results of experimenters may be due to differences in the nature of the fibres, etc. considered. Fibres of materials such as cotton, pressboard, wood, asbestos, etc. will absorb moisture and become conducting. When dry, they are non-conductors, and, since they also have a fairly high electric strength, one would expect their effect upon the B.D.V. of the liquid to be due mainly to flux concentrations, and not to be very large. If, on the other hand, the fibres are intrinsically conducting, then probably they would produce a strong lowering effect upon the B.D.V. independently of moisture. The form in which carbon is dispersed in an insulating liquid is probably such that moisture in small quantities has not very much effect.

## 2. FINE COLLOIDAL SUSPENSIONS

Solids must often exist in liquid insulators as colloidal suspensions, but in small traces it is difficult to separate their effects from those of larger particles considered above. If they are present in larger quantities, other contaminations are likely also to be present, and it will be impossible to distinguish the different effects. There is some evidence that very fine suspensions have little effect upon breakdown, although Spath[1] thinks all sizes of particles are of importance. From some E.R.A. results, it appeared that oil coloured by fine carbon suspension still retains its electric strength. Nor do repeated breakdowns, except after a very large number, seem to have much effect, although fine carbon must be produced: while shaking up the larger settling impurities gives a considerable decrease of the B.D.V. In a colloidal suspension the particles acquire various charges, and the superimposed electric field would have considerable effect. Oelschlager's[2] microscopic observations on the complicated circulation effects of small particles in oil under electric stress show that such particles possess different charges, which appear to vary as they move. We may say that if the particles are large enough the considerations of the previous clauses will apply, while if the suspension is very fine the effect of the suspended particles on the B.D.V. is much less. There is not at present sufficient evidence to decide where the dividing line should be drawn.

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[1] Spath, *Archiv für Elektrotechnik* (30th June 1923).

[2] Oelschlager, *Siemens Zeitschrift* (January 1925).

## (c) Liquid Impurities

Since moisture is much the commonest of liquid impurities, and since its effect has been investigated to a far greater extent than that of other liquids, it is here given first place.

### (i) *Effect of Moisture*

Water may be interspersed in a liquid in the following ways :—

(1) True solution.
(2) Colloidal solution.
(3) Emulsion.
(4) Condensed on solid nuclei, or absorbed by fibres.

In most cases it will probably be present in all four forms unless special precautions are taken. The experimental results will be given and considered from the point of view of the above classification.

### 1. VOLTAGE/MOISTURE CURVES

In the case of ordinary insulating oils the addition of small quantities of water gives an initial rapid fall in the B.D.V. As the amount of moisture is increased the fall becomes slower and the B.D.V. approaches a limiting value. Voltage/moisture curves of the above general characteristics are a feature of the results of all workers. Reference is made to the following : Peek,[1] Hirobe,[2] *G.E. Bulletin* 49701, Flight,[3] Friese,[4] Schroter,[5] Spath.[6] Tests carried out for the E.R.A. show the same features, and some curves are given in fig. 5 and fig. 6.

It has also been found possible in some cases to use such voltage/moisture curves to determine, with moderate accuracy, the humidity of a sample from its B.D.V. There are, however, no laws of general application. Friese [4] has given a formula

$$g=\frac{1{\cdot}1}{W}+20 \quad . \quad . \quad . \quad . \qquad a2$$

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[1] Peek, *Dielectric Phenomena*, p. 154.

[2] Hirobe, Report 25, section iii, Electrotechnical Laboratory, Tokio.

[3] Flight, *B.E.A.M.A. Journal* (February–March 1921).

[4] Friese, *Siemens Science Journal* (March 1922).

[5] Schroter, *Archiv für Elektrotechnik* (March 1923).

[6] Spath, *Archiv für Elektrotechnik* (30th June 1923).

($g$=breakdown strength in kV/cm. tested between cylinders, W=parts of water per 1000), connecting the breakdown strength with the moisture content, which holds, according to him, for several types of insulating oil examined by him.

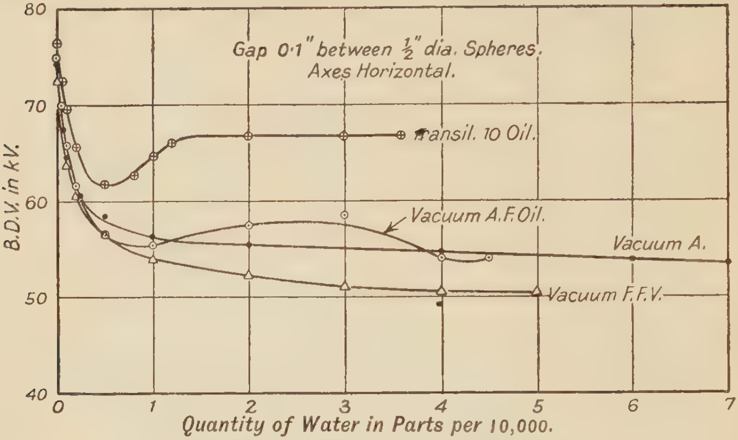

Fig. 5.—Effect of Water on B.D.V. of various Oils.

At the present time, however, neither the breakdown strength nor any other simple quantity can be considered as determining the breakdown properties of a liquid. The exact form of the

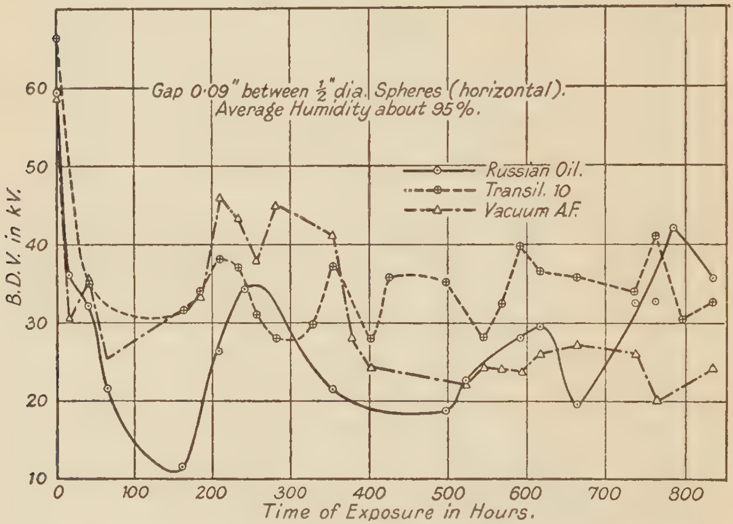

Fig. 6.—Effect of exposure to Damp Atmosphere on B.D.V. of Oils.

voltage/moisture curve depends upon the form of electrodes used. Conversion tables have been suggested for passing from one form of gap to another, but they are empirical and unsatisfactory, since they depend upon the quality of the liquid.

Different liquids react differently to the presence of moisture. Armstrong[1] finds this true among insulating oils of similar composition. The curves in fig. 5 show appreciable differences, although the compositions of the liquids probably differ but little.

### 2. THE SETTLING OUT OF SUSPENDED MOISTURE

When the globules of water become sufficiently large they settle out under the action of gravity. This is a common observation, and the curves in fig. 7, from tests for the E.R.A., illustrate the progress of the settling cloud of moisture acquired by exposure to a humid atmosphere. The B.D.V. of most insulating oils is considerably lowered if the oil is stirred between shots (as found in the E.R.A. investigations). It has been observed that there is, nevertheless, a minimum B.D.V. below which stirring does not lower the strength. In many cases this may be due to dispersion

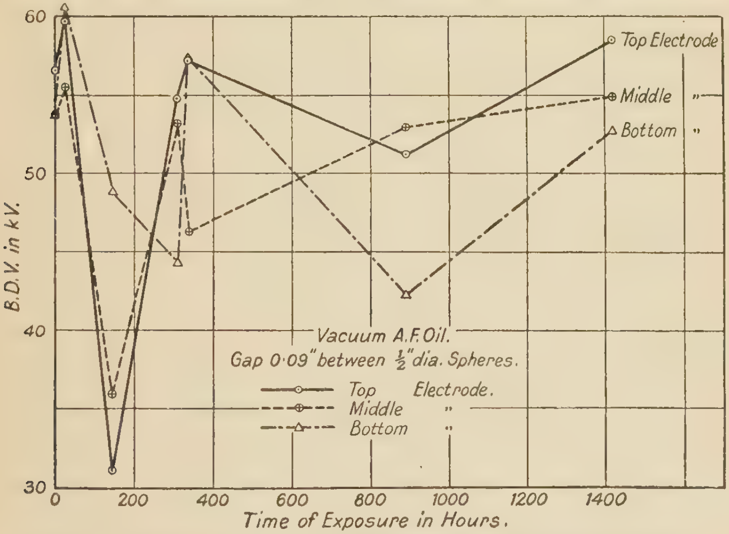

Fig. 7.—Effect on B.D.V. of Oil of the settling of Moisture absorbed from Atmosphere.

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[1] Armstrong, *Electrical World* (27th December 1913).

of moisture, although stirring may also introduce air bubbles. Friese[1] states that there is a critical emulsion of water with oil, and gives an estimate of the size of the particles. We may note here that in some of the E.R.A. work on the effect of moisture, a rotating paddle was used as stirrer. This was found not to have any intrinsic deleterious action on the oil. The possibility of such effects must be taken into consideration in experimental investigations.

### 3. EFFECT OF EMULSIONS

Most of the water present will usually be in the form of an emulsion. The size of the drops is determined partly by the quantity of water available, partly by the electrical charges on them, and therefore by the electric field, and to a smaller extent by the relative surface tensions. As the moisture content increases, the particles increase in size and number.

The work carried out for the E.R.A. on the effect of pure moisture, which has already been mentioned (see fig. 5), may be regarded largely as tests on emulsions. Care was taken to work with pure oil and pure water, so that it seems that water has a considerable intrinsic effect upon the B.D.V. This is Schroter's[2] view, while Hirobe[3] thinks otherwise. Pure water alone gives a reduction in B.D.V. of the order of 30 per cent., which is much smaller than the reduction produced when fibres are present. Accordingly Hirobe and others may have neglected the former reduction and taken the latter as the only effect. That it has been possible to use voltage/moisture curves to predict moisture contents and B.D.V.'s is also in favour of moisture having an intrinsic effect, while the work of the E.R.A. seems definitely to show the existence of deterioration of breakdown strength produced by pure water alone. This deterioration is homogeneous in nature, and it is generally found that when much water is present the variation of individual readings is reduced. If breakdown were due to fibres made effective by the water, a wide variation would probably be observed.

Water globules may form strings and bridges as in the case of solid particles. Under the action of the electrostatic field they may be drawn into the gap and elongated, and may short-circuit the gap. This effect is put forward by Hirobe[1] and Schroter,[2] while Stern[3] has actually observed the formation of liquid strings. Dubois[4] has shown that, in order to give maximum power loss, the length of a water globule should have a critical value, depending upon the cross section and not upon the field strength. The difficulty with his calculation is that it cannot be assumed that maximum power loss is the deciding condition. The determining conditions are uncertain, but surface tension may be of importance. The shape and size of the globule would be determined largely by the surface tension and the electric field, as in phenomena of electrical precipitation. The surface potential energy is the product of the area of the surface and coefficient of surface tension, and tends to decrease the surface. The electrical potential energy is one-half the product of the electrostatic charge and potential, and depends upon the capacity and electric field. Since the capacity increases with the size the potential energy becomes lower, and so the electric field tends to increase the surface. Thus the globules will have to combine or disintegrate until the sum of the surface potential and electrostatic energies are stationary, *i.e.* the total potential energy is a minimum, the globule surfaces being equipotential surfaces for the field. If S is the surface, $\sigma$ the surface tension, $e$ the charge on the globule both intrinsic and induced, V the potential of the equipotential surface forming the globule, the condition for equilibrium is

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[1] Friese, *Siemens Science Journal* (March 1922).

[2] Schroter, *Archiv für Elektrotechnik* (March 1923).

[3] Hirobe, Report 25, section iii, Electrotechnical Laboratory, Tokio.

$$\sigma\, d\mathrm{S} + \tfrac{1}{2} d(e\mathrm{V}) = 0 \qquad . \quad . \quad . \quad . \quad a3$$

Dubois, however, considers a uniform field undistorted by the presence of the globule. Such assumptions preclude effects of the nature just considered, since the globule would not have an equipotential surface.

The liquid bridge theory accounts for differences with different electrodes, but presents difficulty in explaining the variation of

[1] Hirobe, Report 25, section iii, Electrotechnical Laboratory, Tokio.

[2] Schroter, *Archiv für Elektrotechnik* (March 1923).

[3] Stern, *E.T.Z.* (30th March 1922).

[4] Dubois, *A.I.E.E.* (1922).

extreme values and the limiting minimum value of the voltage/moisture curve. Water beyond a certain quantity appears to settle out, but the minimum of B.D.V. is still obtained with certain modes of stirring. With pointed electrodes globules may condense round the points, decreasing the curvature and raising the B.D.V. Hirobe (*loc. cit.*) and Miner[1] have observed this increase of B.D.V. (see figs. 8 and 9). It may also be noted that the form of the field probably exerts a considerable influence on the size of the particles of the emulsion. Moisture may also be deposited on the walls of the container if the material is hygro-

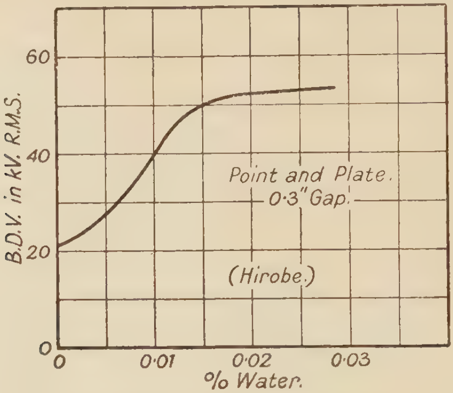

Fig. 8.—Effect of Moisture on Points.

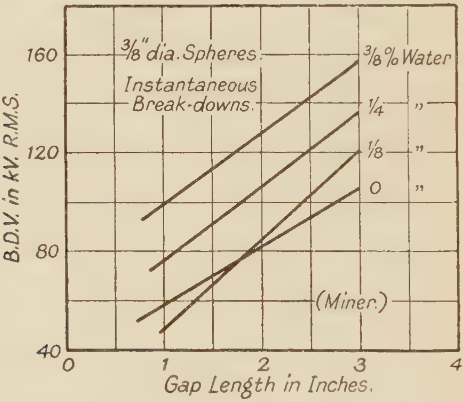

Fig. 9.—Moisture in long Gaps.

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[1] Miner, *A.I.E.E.* (April 1927).

scopic, whence it may be introduced into the liquid by shaking or stirring. No marked difference was found between silica and glass containers, although silica is much less hygroscopic than soft glass.

### 4. WATER CONDENSED ON NUCLEI OR ABSORBED BY FIBRES

The theory of breakdown along strings of moist fibres has already been described in paragraph *b* (ii). It is well known that oil containing moisture and fibres gives practically the lowest breakdown values. This has been confirmed by work for the E.R.A., but the main effect is ascribed by some to the moisture, and by others, *e.g.* Hirobe,[1] to the fibres. Investigations by the E.R.A. have shown that both moisture and solid particles must be present for the worst effect to be developed. As mentioned above, emulsified water in small quantities produced a decrease of about 30 per cent. in the B.D.V. Cotton and pressboard fibre gave a similar decrease in dry oil (figs. 1*a*, 3*a*), a limiting value being reached after about 50 mg. of added fibre per 10,000 c.c. If, however, moisture is added to oil containing fibres the decrease is more rapid and much larger, a reduction to a seventh in the B.D.V. of the pure oil being produced with only small quantities of fibre and moisture present (figs. 10, 11, 12). Less cotton fibre than pressboard fibre was required to lower the B.D.V. to 10 kV on 0·1-in. sphere gap. Again, a similar lowering is produced if fibre is added to moist oil instead of water being added to oil containing fibres; the decrease is more rapid with larger initial quantities of moisture in the former case or of fibre in the latter case (figs. 2 and 3).

Rather different results were obtained with carbon particles. In dry oil a slow but apparently steady decrease in the B.D.V. occurred (fig. 4). With moist oil the decrease was larger and quicker the greater the quantity of water, but was not so large as with fibres and showed less tendency to reach a minimum value (fig. 4). When water was added to oil containing carbon only, a small and rapid lowering was observed, the effect being greater the more carbon present (fig. 12).

Water thus appears to be absorbed by fibres, either swelling

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[1] Hirobe, Report 25, section iii, Electrotechnical Laboratory, Tokio.

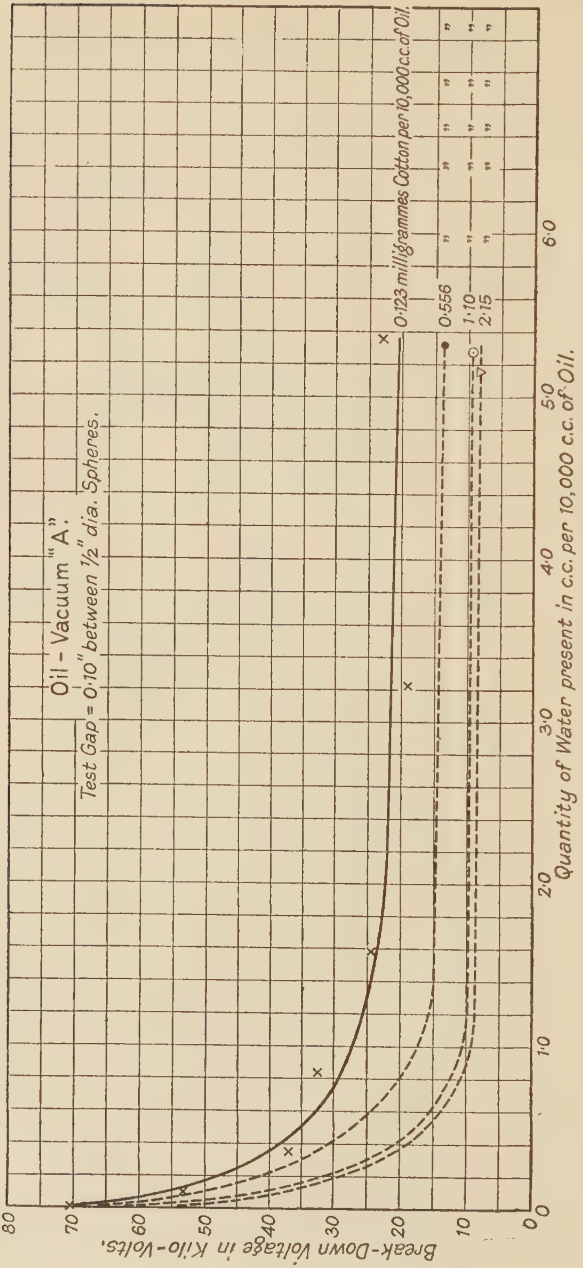

Fig. 10.—Effect of Added Water on the B.D.V. of Insulating Oil containing a Constant Proportion of Cotton Fibre.

the fibres and making them conducting, or forming non-rigid globules around them, which elongate in the electric field. The fibres rapidly absorb the moisture up to a critical amount—subsequent addition has little effect. If moisture condenses round nuclei, *e.g.* carbon particles, there is less effect, at any rate initially, than with fibres. This may be due to the fact that the moisture is not absorbed but condensed, a process which would be slower. More moisture is required to give a saturation effect.

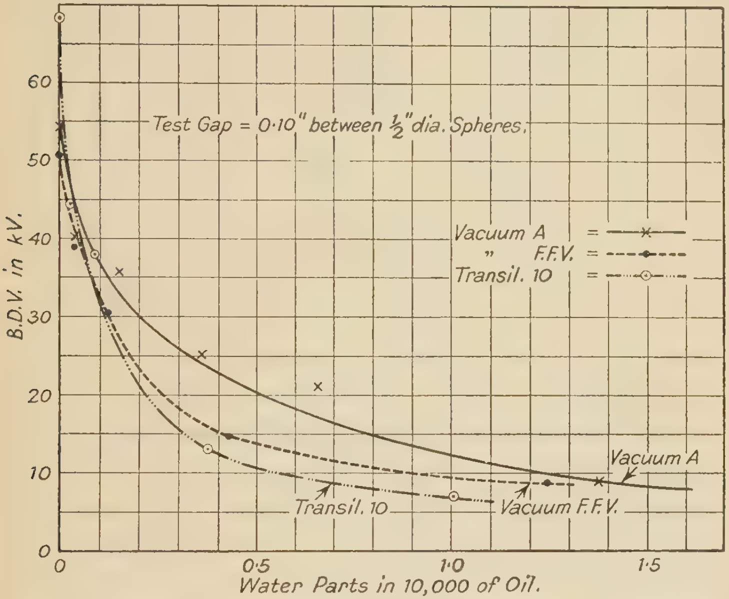

FIG. 11.—Effect of Water on the B.D.V. of Oil containing a Considerable Quantity of Cotton Fibre.

### 5. WATER AS A TRUE OR COLLOIDAL SOLUTION

It is probable that only very small traces of moisture actually dissolve in insulating oils, and other liquid insulators should be examined for the effect of dissolved water. Under the action of the electric field a coarser suspension might be formed through separation out of a colloidal solution. If present, water in solution would give a homogeneous deterioration, and might account for some of the initial decrease of B.D.V. when very small quantities of moisture are added. The main difference

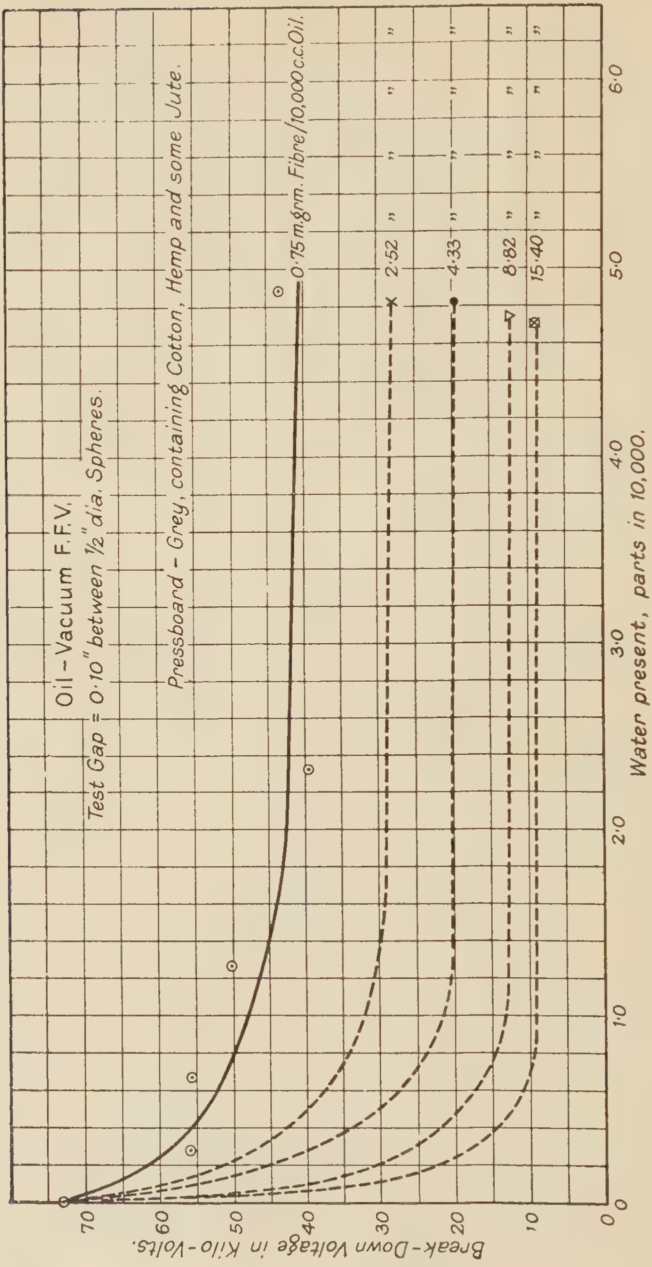

Fig. 12.—Effect of Added Water on B.D.V. of Insulating Oil containing a Constant Proportion of Pressboard Fibre.

between water and other liquids in the present case lies in the relatively high conductivity of the former under normal conditions. Thus water in solution would increase the conductivity, and so might lower the B.D.V. (see Chapter VIII for views on the relation of conductivity to B.D.V.). One would expect considerable differences as the water was more and more pure, but this effect may have been masked by other factors. Water frequently dissolves in or is absorbed by impurities already present in the liquid, producing a different homogeneous impurity, but the effect of such conditions has not been adequately investigated.

### 6. SUMMARY

Moisture may lower the B.D.V. of an insulating liquid in the following ways :—

(*a*) By the intrinsic effect of solution.
(*b*) By the intrinsic effect of emulsion.
(*c*) By the formation of strings, bridges, etc. in an emulsion.
(*d*) By absorption in fibres or condensation round nuclei.
(*e*) By dissolving other impurities, particularly electrolytes.

The effect of (*a*) is not understood and probably small. Emulsified water produces a limiting fall of B.D.V. of about 30 per cent. for pure oils,[1] with fairly small quantities of water. This is due partly to an action such as (*b*) and partly to (*c*), but the relative importance of the two mechanisms is uncertain. Water in conjunction with fibres gives the lowest breakdowns – small quantities of the two reducing the B.D.V. to a fraction of the pure oil B.D.V. When condensed round nuclei the reduction of B.D.V. is much slower. The effect considered under (*e*) has not been accurately investigated, but is likely to be considerable if the water and impurities are present in sufficient quantities.

### (ii) *Effect of other Liquids*

The effect of contamination of insulating liquids by other liquids has not been investigated to any extent, so that much of the evidence is indirect. We may classify the effects into those due to dissolved or intimately mixed liquids and those due to coarser mixtures.

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[1] This figure applies to conditions of fig. 5.

### 1. LIQUIDS INTIMATELY MIXED

There is no available evidence as to the effect of intimately mixed liquids upon the electrical strength of insulating liquids other than the insulating oils of commerce. Even in the case of insulating oils there is little direct evidence. It appears that the chief conducting liquids found in oils are the acid products of sludging—organic acids of different compositions. These acids have a lowering effect upon the electric strength. At present it cannot be stated whether their effect is chiefly due to their conductivity or to some other property. As has been said before, it is thought by some that the direct current conductivity of an insulator is a valuable guide to the electric strength.

A mixture of one insulating liquid with another will have a strength intermediate between the strengths of the components. There is no accurate data in the case of liquids with widely differing strengths and readily soluble in each other. Insulating oils dissolve one another to some extent, and since ordinary insulating oil is a mixture of several oils there must be a certain amount of solution. Pure simple oils, however, do not differ very greatly in electric strength either amongst one another or as compared with mixtures. Accordingly it would seem that in the case of good liquid insulators no characteristic effects are produced by the solution or intimate mixture with them of insulating liquids of comparable quality. In practice, the most important point would be the relative freedom of either liquid from other impurities.

### 2. EMULSIONS

In the case of suspended liquid impurities, many of the considerations developed for water also apply. If the suspended liquid is of higher specific inductive capacity than the medium the globules will be attracted to the stronger parts of the field and form liquid bridges and chains, and breakdown will take place as described in paragraph (*b*) (ii) above. This is the view of Hirobe,[1] Peek,[2] and many others.

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[1] Hirobe, Report 25, section iii, Electrotechnical Laboratory, Tokio.

[2] Peek, *Dielectric Phenomena*, p. 154.

On the other hand, in many cases the suspended liquid may itself have insulating properties as good as or better than the medium. If we have layers of dielectrics of strength $g_r$ and S.I.C. $\epsilon_r$ in a uniform field, the dielectric for which $\epsilon_r g_r$ has the least value will break down first. Roughly, therefore, if $\epsilon g$ for the suspended liquid is greater than $\epsilon g$ for the medium, it is unlikely that a liquid chain itself will prove a weakness ; although, of course, the term electric strength only applies to the particular cases considered, since both the B.D.V. and maximum stress for breakdown are determined by the nature of the field.

Thus we can divide these bridging and similar effects into two classes—that where the suspended liquid will break down and so destroy the medium in its neighbourhood, and that where the suspended liquid is itself relatively stronger than the medium.

In the latter case there is divergence of opinion as to the effect to be expected. Schroter [1] considers that the flux concentration may result in a pilot spark, but not in complete breakdown. The latter requires the presence of moisture. In the case of otherwise pure liquids it seems reasonable to suppose that, if pilot sparking is liable to occur, complete breakdown will happen at a lower voltage than if the oil were completely pure and no pilot sparks took place. According to Schroter the spark avoids the liquid chain or string. We may explain this by considering that the flux concentration produces large variations in the field. With impure oil, *i.e.* oil with other impurities such as water globules or fibres, the particles which are actually a weakness are driven away from the liquid chain, since in the neighbourhood of the chain the gradient of the electric force, although large, is perpendicular to the force itself, giving a zero resultant force on a dielectric particle. In this way the spark due to the other impurities avoids the chain. If the oil were pure except for the liquid of which the chain is composed, the oil would probably break down along the chain where the absolute value of the force was greater.

Chains of liquid of high specific inductive capacity have actually been observed by Brückmann.[2] Particles of liquid of lower specific inductive capacity than the medium would be expected to avoid the gap, and so should not have much effect. This point has not been adequately investigated. It must also be remembered that the field has a considerable influence upon the nature of the suspended particles. As was suggested in the case of water, variations may be expected from this cause with different forms of field. It would be interesting to test what effect the conductivity of the contaminating liquid had upon the breakdown. This has already been mentioned in the case of water.

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[1] Schroter, *Archiv für Elektrotechnik* (March 1923).

[2] See Correspondence, *E.T.Z.* (1922).

Valuable information might be obtained by investigating the effect of suspensions of good insulating liquids, since in this case a liquid bridge would not shortcircuit the gap. One uncertainty would thus be removed. In such an investigation it must be borne in mind that there may be a conducting surface layer round the liquid string, due to adsorption of electrolytes from the medium.

## (*d*) EFFECT OF GASES

### (i) *Dissolved Gases*

Insulating liquids dissolve gases to varying extents. In the majority of cases this solution, except where chemical action takes place, is small. For transformer oils volumes of gases varying from 9 per cent. of oil volume for nitrogen and hydrogen to 108 per cent. of $CO_2$ are absorbed at atmospheric pressure and temperature.[1] Although the amount of dissolved gas by weight is small, yet it is difficult to remove, and it is still more difficult to prevent solution from taking place. It is difficult to say what direct effect dissolved gases have upon breakdown, since some mechanism must be assumed. Bubbles of gas would be very liable to form if the liquid were subjected to changes of temperature and pressure, or to agitation. On an ionic theory of breakdown, or any theory involving high local conductivity, bubbles would form more easily, the gas in them breaking down and decomposing the oil. The indirect effect of dissolved gases may be important. Oxygen dissolved in insulating oils is one of the most important agents in sludging. Reducing and inert gases, however, seem to impede sludging, and so their indirect effect can be considered beneficial. It is supposed that dissolved $CO_2$ may, in conjunction with the moisture present, have a deleterious effect. In the majority of cases, however, oxygen is probably by far the most important.

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[1] Rodman and Maude, *Journ. Am. Electro. Chem. Soc.* (1925).

### (ii) *Free Gases*

Under this heading are included gases in the form of bubbles and gases caught in fibres, etc. The presence of gas bubbles from dissolved gases, etc. has been suggested by Hirobe, and it is well known that many of the earlier forms of centrifuge were unsatisfactory, owing to the aeration caused by them.

A bubble of gas, having a low specific inductive capacity, would, on the whole, be impelled away from the gap. However, some would be present in the gap at any given time owing to chance motion and also to the fact that the electrically stressed liquid of the gap is favourable to their generation. Owing to the low strength, ionisation would easily take place in them, resulting in deterioration of the oil and subsequent breakdown. It has been suggested that the mechanism of breakdown is always analogous to this. (See Chapter VIII.) There is, however, no doubt that gas bubbles cause a considerable lowering of the B.D.V. Probably the disturbing effect in some E.R.A. tests caused by stirring with a glass rod between shots was due to the formation of bubbles. It is well known that aeration should be carefully guarded against.

If the fibres in the liquid become loaded with gas, then the specific inductive capacity may be such that they are drawn to the gap, while since their electric strength is still low they will break down very easily. Spath[1] has suggested this loading of fibres with air as an important cause of breakdown. It seems probable that bridges of fibres loaded with air should, with the possible exception of conducting strings, give the lowest breakdown values.

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[1] Spath, *Archiv für Elektrotechnik* (30th June 1923).

# CHAPTER II

## INFLUENCE OF FORM OF ELECTRIC FIELD

### (*a*) Uniform Field

### (i) *Introductory*

The ideal uniform field is the field between two infinite parallel charged planes, but it is not easily realisable in practice. With two plane discs, whatever the size used, the flux concentration at the edges is somewhat analogous to that obtained by placing a needle gap in parallel. Accordingly, the flux density must be carefully graded at the boundaries. This is achieved generally in one of four ways:

(1) By flaring out the edges and sometimes by bending them sufficiently to give a re-entrant section.

(2) By using a thick electrode and smoothly rounding off the edges with a fairly small curvature—a good example is the mushroom-shaped electrode used in Germany.

(3) By using spheres at spacings small compared with their radii.

(4) By using concentric cylinders (with flared ends), with very little difference between the radii.

In method (3) the assumption is made that a homogeneous fluid will break down where the stress is greatest. This is not necessarily true, since, for example, the extent of the region of stress is important; the question really depends upon the assumption of some specific type of mechanism of breakdown. If the first assumption is justifiable, then, if in the neighbourhood of the maximum stress the field is uniform, the breakdown can be said to be of a uniform field type. With spheres it is difficult to say exactly at what spacings this is true. However, when the ratio of spacing to radius is less than 0·15, the maximum stress at the surface does not exceed the mean stress across the gap by more than 3 per cent., so that the variation from uniformity of the field is within the probable experimental error. In Peek's opinion the sphere gap gives an effective uniform field for much larger spacings than this.

In the present section an account is given not only of the variations shown by the mean values of the B.D.V., but also of extreme individual readings, both high and low, where the figures are available. In the first place, there is a possibility that the extreme readings may be characteristic of some definite type of breakdown; for example, the highest readings of a very pure liquid might be those which occur independent of heterogeneous impurities. In the second place, the lowest readings are of practical importance, since it is the lowest probable strength of a given insulation which determines the design of the apparatus in which it is employed.

### (ii) *Pure Liquids*

The term pure liquids as used in this work includes liquids whose breakdown strength is high. It is difficult to say exactly how pure an insulating liquid is in a particular case, as many experimenters have not given details of the method of purification. In dealing with pure liquids we must also omit results obtained from the concentric cylinder gap. From its nature any impurity in the sample taken is practically bound to have its effect, and since we are endeavouring to investigate the properties of homogeneous liquids, observations on such a gap must be neglected. It may be mentioned that by taking extreme precautions Friese[1] has obtained high values with the cylinder gap. The general opinion is that the B.D.V. has a linear relation with the gap setting. This seems to be the case, particularly if the highest individual readings are taken. This law appears to hold for practically all liquids examined.

We may express this by the formula

$$V=A+Bl \quad . \quad . \quad . \quad . \quad b1$$

where $V$=B.D.V. in R.M.S. kilovolts, $l$=gap setting in cm., A and B are constants.

For small thicknesses of liquid the law

$$V=Al^n \quad . \quad . \quad . \quad . \quad b2$$

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[1] Friese, *Siemens Science Journal* (March 1922).

often gives good agreement also (where $n$ is a constant less than unity).

A table of results by different experimenters is given in illustration of $b1$. In each case V=B.D.V. in kV eff., and $l$=gap length in cm.

*Peek*[1] (25 cm. spheres at small spacings)—

$$V=14{\cdot}15+100l \text{ (good oil).}$$

*E.R.A.*:

1-in. diameter spheres at small spacings—

Highest values $V=14+187l$ (see fig. 13).
Mean values $V=9+174l$ (see fig. 13).

2-in. spherical surfaces at small spacings—

Highest values $V=10+193l$ (see fig. 13).
Mean values $V=3+181l$ (see fig. 13).

The above E.R.A. results are on oils of very high purity giving a mean B.D.V. of about 60 kV on a standard gap set at 0·1 in. For the purposes of comparison some results on a good but less pure oil, giving about 47 kV on same gap, are given:

1-in. diameter spheres—

Highest values $V=11{\cdot}5+106{\cdot}5l$ (see fig. 14).
Mean values $V=9{\cdot}5+88{\cdot}7l$ (see fig. 14).

2-inch spherical surfaces—

Highest values $V=8{\cdot}5+118l$ (see fig. 14).
Mean values $V=8+100{\cdot}5l$ (see fig. 14).

*Sorge*[2] (purified oil)—

Highest values $V=10{\cdot}5+180l$ (see fig. 15).
Mean values $V=9+155l$ (see fig. 15).
Xylol $V=3{\cdot}5+433l$ (see fig. 15).
Hexane $V=5{\cdot}5+234l$ (see fig. 15).

*Spath*[3] (oil heated and filtered hot)—

$$V=7+186l \text{ (see fig. 16).}$$

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[1] Peek, *Dielectric Phenomena*, p. 156.

[2] Sorge, *Archiv für Elektrotechnik*, 1924.

[3] Spath, *Archiv für Elektrotechnik* (30th June 1923).

It is interesting to note that in those cases where the oil is known to have been very carefully purified, as in the case of the E.R.A. tests, Sorge's work and Spath's work, the values of the parameters A and B in the formula are not very different. Particularly is this the case with the constant B, which gives values from the sources mentioned of 187, 193, 180, 186 kV/cm.

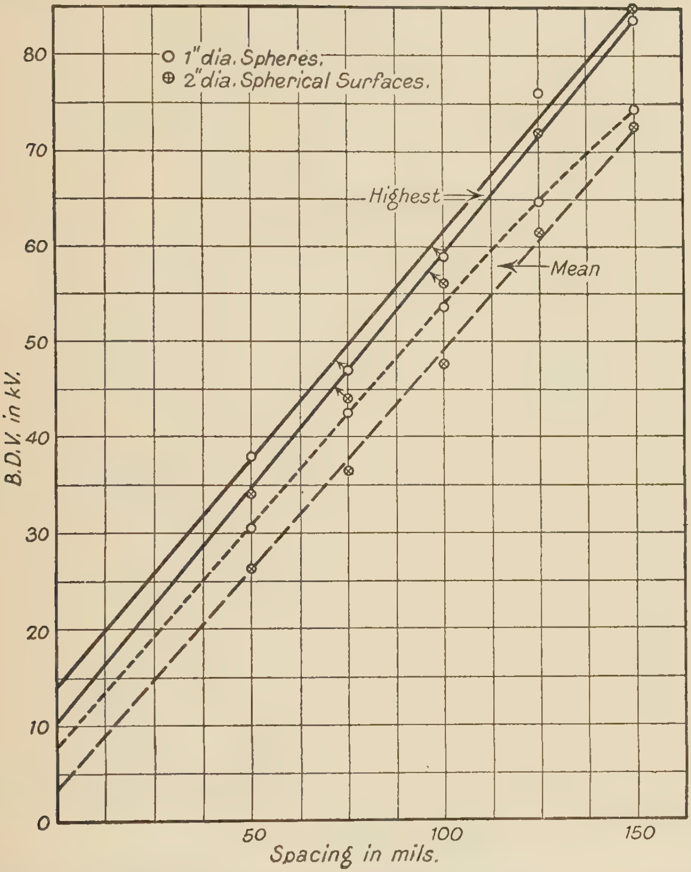

FIG. 13.—Test Results on High Purity Oils (60 kV. approx. on 0·1-in. Gap). Field nearly Uniform.

B may be compared with the "breakdown strength," since the equation *b*1 may be written

$$g = \text{strength} = \frac{V}{l} = \frac{A}{l} + B \qquad . \qquad . \qquad . \qquad b3$$

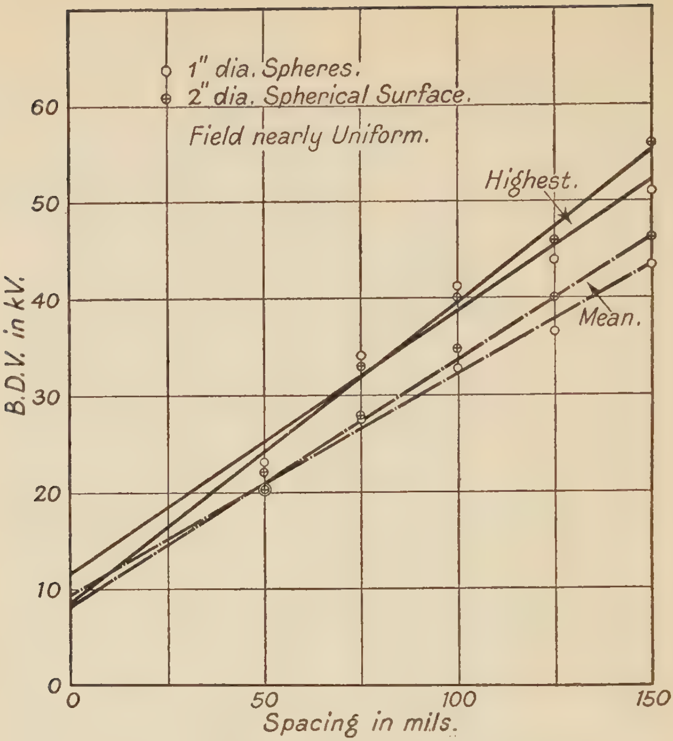

Fig. 14.—Test Results on Good Oils (47 kV. on 0·1-in. Gap).

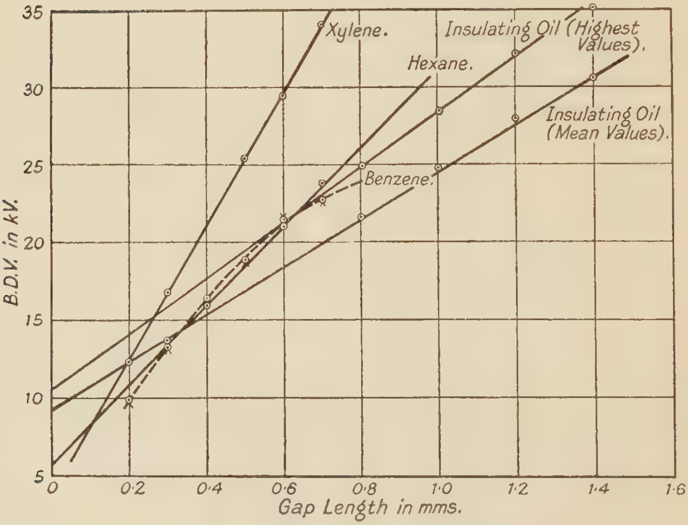

Fig. 15.—B.D.V. of Different Oils in Uniform Field (Sorge).

On the other hand, when different qualities of the same liquid are examined, B often varies more than A. This is well illustrated by Spath's work. He tested oil at different stages of purification, and it is seen (fig. 16) that the B.D.V./spacing characteristics are straight lines, except for unpurified oil, which intercept the voltage axis in the same region. This also appears in some E.R.A. tests on oils of two qualities. Although the percentage changes in A and B in passing from one quality of oil to another are about the same, yet considering the small absolute magnitude of A, and that the percentage variation of individual readings is large at small spacings, it certainly appears that A varies less than B.

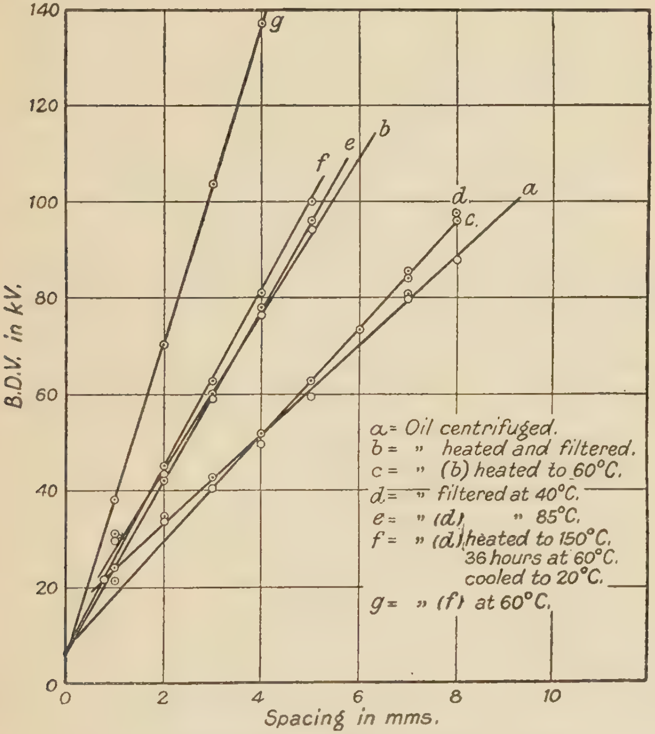

FIG. 16.—Results by Spath on Oil of different Purities.

As may be observed from fig. 15, Sorge's results with benzene show anomalous variations.

### (iii) *Mean and Lowest Readings obtained with good Insulating Liquids*

The mean B.D.V.'s with good insulating liquids have a linear relation with the spacing as mentioned above (see, for example, figs. 13, 14, 15, 16). In fig. 17 are plotted the lowest readings for spheres at small spacings from E.R.A. tests. In the case of the purer oil the lowest readings lie on straight lines, which pass close to the origin but above it. Fig. 17 also shows the lowest readings for the less pure oils used in the above tests. These readings lie on characteristics which show a curvature towards the abscissæ base. The curves for the two sizes of electrodes merge at the lower spacings, and might reasonably be produced to pass through the origin, thus indicating a constant electric strength at smaller spacings.

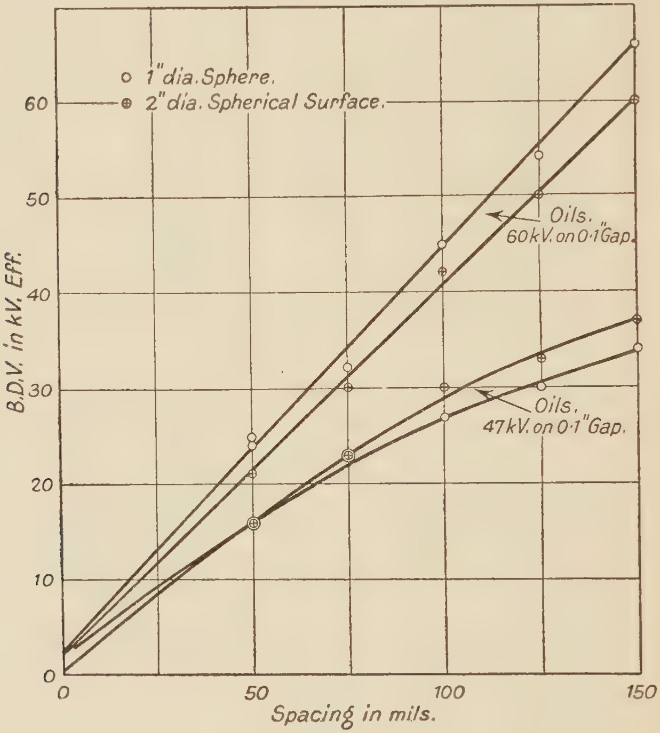

FIG. 17.—Lowest Reading for Good Oils.

In general, for a uniform field produced by electrodes which are immersed in and do not surround the liquid (as in the cylinder gap), the mean B.D.V./spacing curve will not differ much from a straight line. When the variation of individual readings from the mean is considered it is found that, on the whole, the variation increases with the purity of the liquid.

### (iv) *Impure Liquids*

With impure liquids the mean B.D.V. often gives a linear relation with the spacing (as in fig. 16 and fig. 18), but sometimes shows a curvature downwards, the B.D.V. falling short at higher spacings from the values required for a linear law. It is, however, difficult to obtain readings corresponding to uniform fields, since the usual electrodes approximating to a uniform field are spheres, and they are not often used at spacings so small that the field can be taken as uniform. Accordingly, the departure from a straight line may be due to the variation of the form of the field. On fig. 19 are plotted lowest individual readings from tests for the E.R.A. These also lie on straight lines, passing near the origin but below it. We have already observed that the lowest values for good oils lie on a straight line passing near but above the origin, so that these values seem to vary about a line passing through the origin, which would

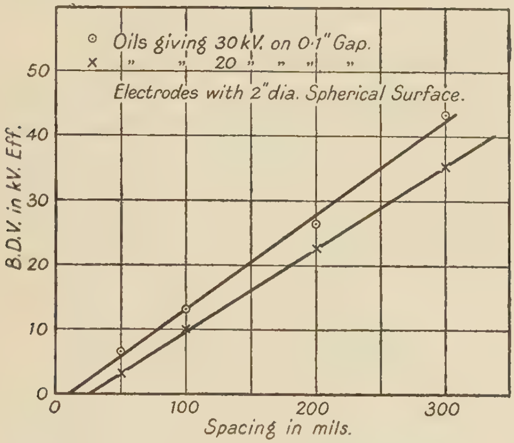

Fig. 18.—Mean B.D.V. of Impure Oils.

indicate a constant electric strength. The point is mentioned in Chapter VIII. If breakdowns in impure liquids are largely due to bridges, one would expect greater variations between results at the higher spacings than at the lower, owing to greater uncertainty due to circulation and effective volume under test. It seems that in some cases such an effect is observed.

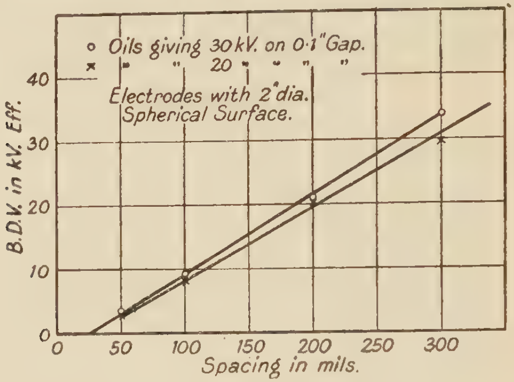

FIG. 19.—Lowest Values for Impure Oils.

### (v) *Effect of Area of Electrode*

If breakdown is often due to the effect of heterogeneous impurities, then the larger the cross section of the uniform and strongest part of the field the greater should be the number of low breakdowns. In E.R.A. tests the mean B.D.V. certainly decreased as the spheres used became larger. This nevertheless does not seem to be due to a greater number of low breakdowns but to a general decrease on all shots. The mean curve shows rather anomalous variations for the largest spheres. In any case the decrease is small, and it is difficult to draw definite inferences.

The general opinion is that the B.D.V. decreases as the size of the electrode increases. There is no definite evidence of a regular decrease and the nature and amount varies with the liquid used. With pure liquids there does not seem to be much variation, but as uniform fields have seldom been used in the investigation of this matter, only tentative statements can be made.

If, however, an electrode of very large area is used, as in the cylinder gap, the B.D.V. is considerably reduced. Here, of course, the breakdown will always be characteristic of the weakest part of the oil. Such results are accordingly not directly comparable with those obtained with electrodes permitting free circulation, such as have hitherto been considered. An exhaustive determination of the effect of electrode area would be of value, but it would be necessary to use uniform fields with areas of sizes ranging from that presumed for the sphere gap to the magnitude of the area of the cylinder gap of the Allmanna Svenska Elektriska Aktiebolaget.

### (vi) *B.D.V. and Electric Strength*

On the Continent and occasionally elsewhere the quality of a liquid has been assessed by its breakdown strength or maximum gradient at breakdown. In the case of a uniform field the gradient in the strongest part of the field is constant.

If the B.D.V. follows the linear law

$$V=A+Bl \quad . \quad . \quad . \quad . \quad b1$$

(V=B.D.V., $l$=gap length), the gradient follows the law

$$g=B+\frac{A}{l} \quad . \quad . \quad . \quad . \quad b3$$

If A is positive, as is generally the case with a good average insulating liquid, the gradient $g$ decreases with increasing gap length, bending hyperbolically to a constant minimum value B. This constant B may be taken as a criterion of the strength of the liquid, as the critical voltage calculated on such a basis for a given gap will never exceed the actual B.D.V. The closeness of the approximation will depend upon the magnitude of A; if the latter is large the critical voltages calculated from the minimum strength will be much too small, and give a false idea of the average strength. If A appears to be negative, as may happen with very impure liquids tested over a small range, the gradient rises hyperbolically towards a constant maximum given by B in the range considered. Accordingly, if a wider range of spacings were examined, the above portion would appear as an anomalous maximum on the curve and would be neglected.

## (*b*) SPHERE GAP

### (i) *Purified Liquids*

#### 1. MEAN B.D.V.

The curves of mean B.D.V./spacing for a given sphere diameter are, for a wide range at smaller spacings, practically straight lines. For higher spacings the curves separate, and higher voltages are required for the larger spheres. There is, however, no great uniformity in this. In results of E.R.A. tests there seems no great regularity in the variation with the size of sphere, and larger spheres appear to give lower breakdowns with good oils. The spacings employed are, however, not very large, and the field in all cases is not much removed from the uniform. Peek[1] finds an increase in voltage with increase in sphere

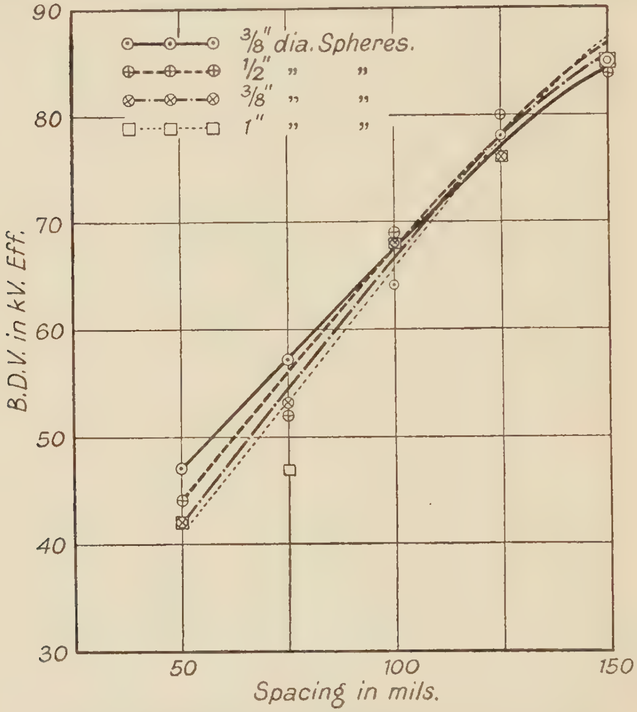

FIG. 20.—Highest Readings for Breakdown of very Pure Oil between Spheres.

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[1] Peek, *Dielectric Phenomena*, p. 156.

diameter, and says this is generally obtained with good oils when the spacing is comparable with the diameter. In figs. 20 and 21 are given voltage/spacing curves from different authorities for various sizes of spheres.

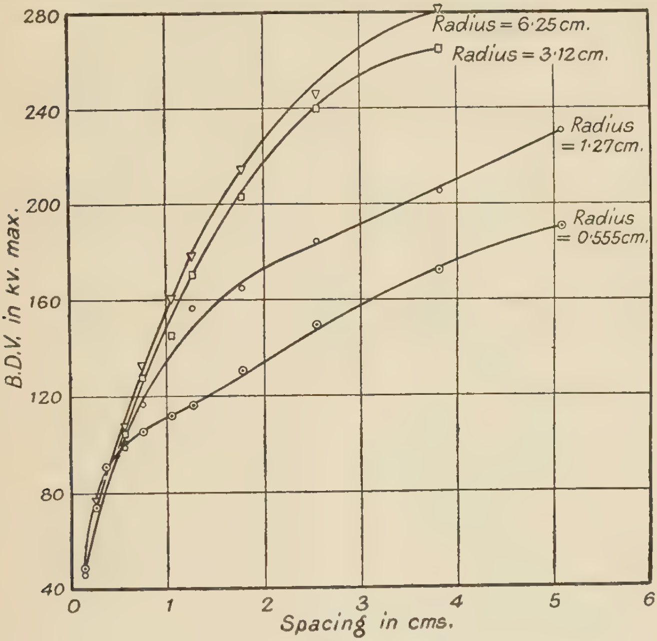

Fig. 21.—B.D.V. between Spheres with Pure Oil (Peek).

## 2. BREAKDOWN GRADIENT

If we take results for good oils, and where possible the highest readings (as in E.R.A. tests), and then calculate the breakdown surface gradients, some interesting curves are obtained. This has been applied to results given by Hirobe,[1] Peek,[2] the E.R.A., and Sorge[3] (see figs. 22–26). Hirobe's results seem anomalous. One set of Peek's results gives a hyperbolic curve. The E.R.A. tests on 1-in. spheres give a curve falling to a constant limit for the vertical arrangement, while a very distinct minimum occurs for the horizontal gap. On the other hand, the tests on ½-in. and ¼-in. spheres show a well-marked minimum when the gradient is plotted against the ratio of spacing to radius, the results with horizontal gap being lower than with the vertical. However, the gradient for ¼-in. spheres appears to be lower than for ½-in. spheres; the reverse is the case with gases. Sorge's results also lie on a curve of hyperbolic form, but when compared with results for uniform field and points, the gradient decreases with increasing curvature as for gases. This is especially interesting, as Sorge worked with simple liquids as well as with oil. Wellauer[1] also gives curves bending to a constant minimum in value, but the formula he used to calculate the gradient appears to be inaccurate. If accurately calculated his curves would show a minimum at a certain spacing. Other sets of results obtained by the E.R.A. and Peek[2] for spheres of different sizes have been further examined. In the case of the former, oils of very much the same purity were used for each set of electrodes and

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[1] Hirobe, Report 25, section iii, Electrotechnical Laboratory, Tokio.

[2] Peek, *Dielectric Phenomena*, p. 156.

[3] Sorge, *Archiv für Elektrotechnik* (1924).

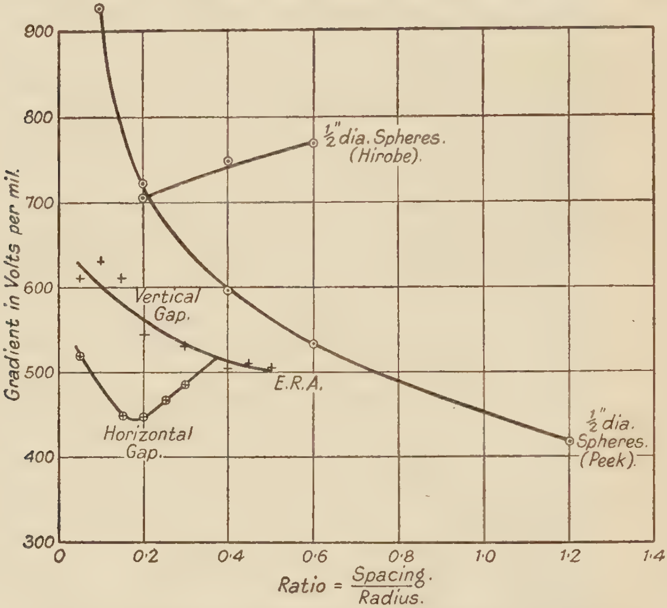

FIG. 22.—Breakdown Surface Gradients for Spheres in Pure Oils.

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[1] Wellauer, *Schweiz. Electrotechnischer Verein* (April 1925).

[2] Peek, *Dielectric Phenomena*, p. 156.

the highest values have been taken. The curves when maximum gradient is plotted against the ratio of spacing to radius are in all cases hyperbolic in form, but for $\frac{3}{8}$-in. spheres there is an indication of a minimum. For the larger spheres the values of the ratio are not large enough to show whether a minimum occurs for spheres of other sizes.

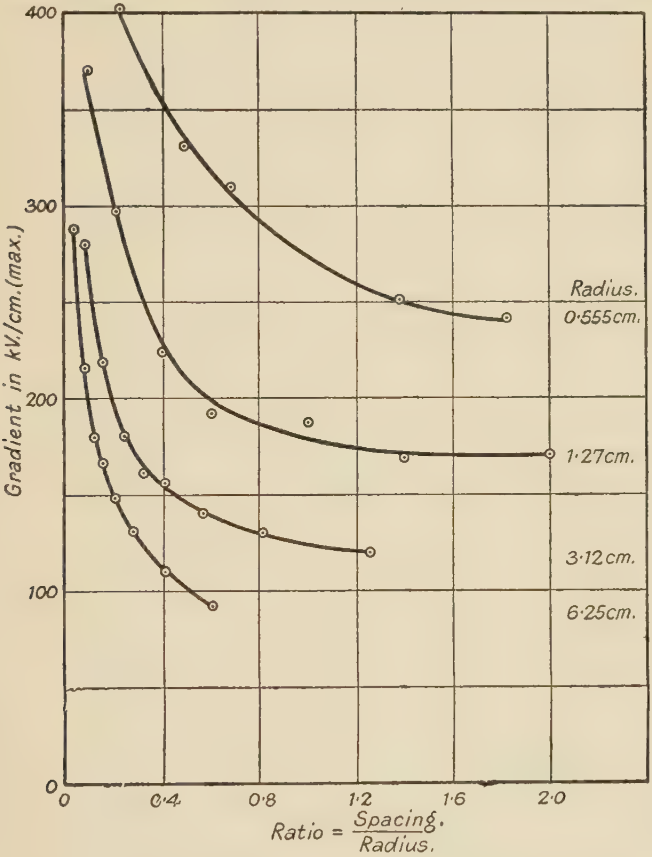

Fig. 23.—Breakdown Surface Gradient from Results by Peek.

For a given value of the ratio of spacing to radius the gradient depends upon the radius in the same manner as for gases, viz.,

$$\text{gradient at surface}=\mathrm{R}=\mathrm{A}+\frac{\mathrm{B}}{\sqrt{a}} \qquad . \qquad . \qquad 64$$

(A and B are constants, $a$=radius), (see figs. 27 and 28).

The constants A and B vary rather widely, particularly with

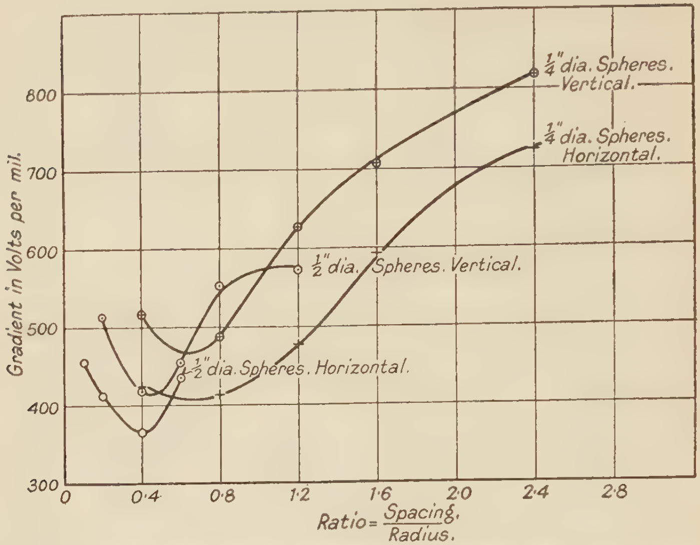

FIG. 24.—Breakdown Surface Gradients for Horizontal and Vertical Gaps.

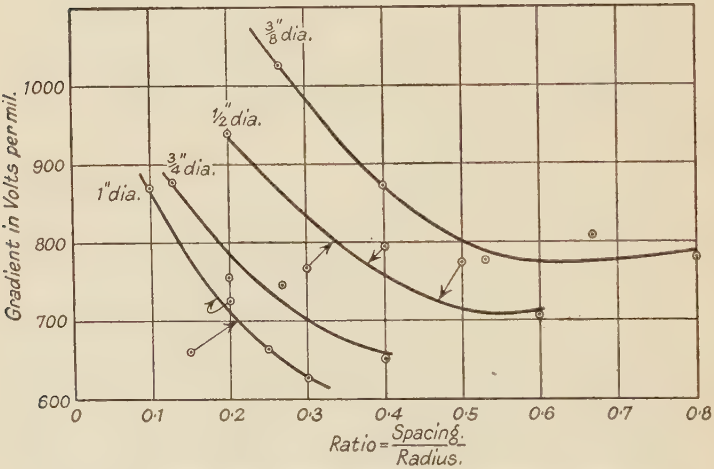

FIG. 25.—Breakdown Surface Gradient for Spheres in Pure Oils.
(Results from fig. 20.)

Peek's values. This may be due to the fact that Peek took mean results instead of the highest.

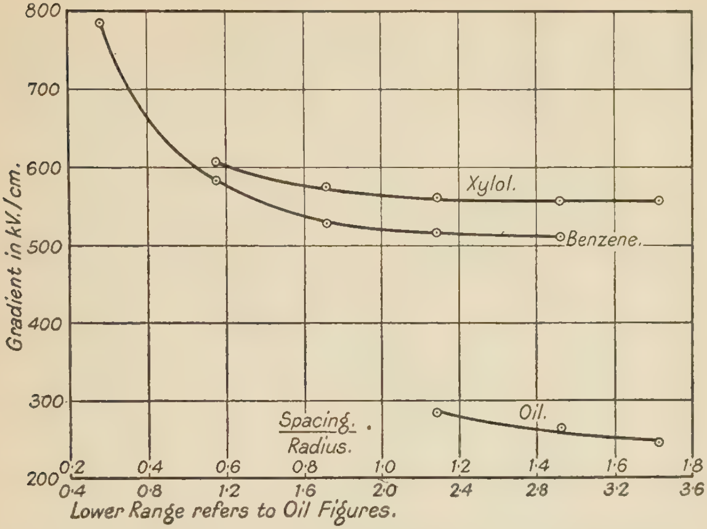

FIG. 26.—Breakdown Surface Gradients for 7 mm. Radius Spheres in Various Liquids (Sorge).

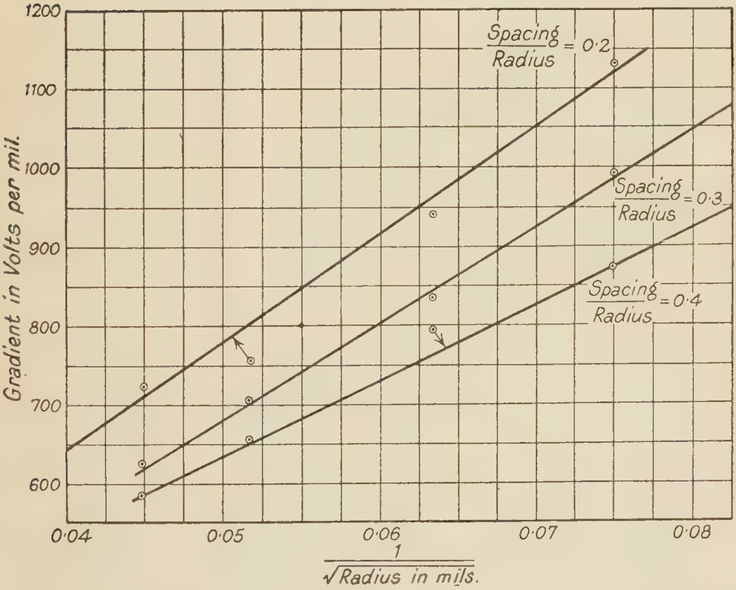

FIG. 27.—Variation of Breakdown Gradient with Radius and $\frac{\text{Spacing}}{\text{Radius}}$.

(Points taken from fig. 25.)

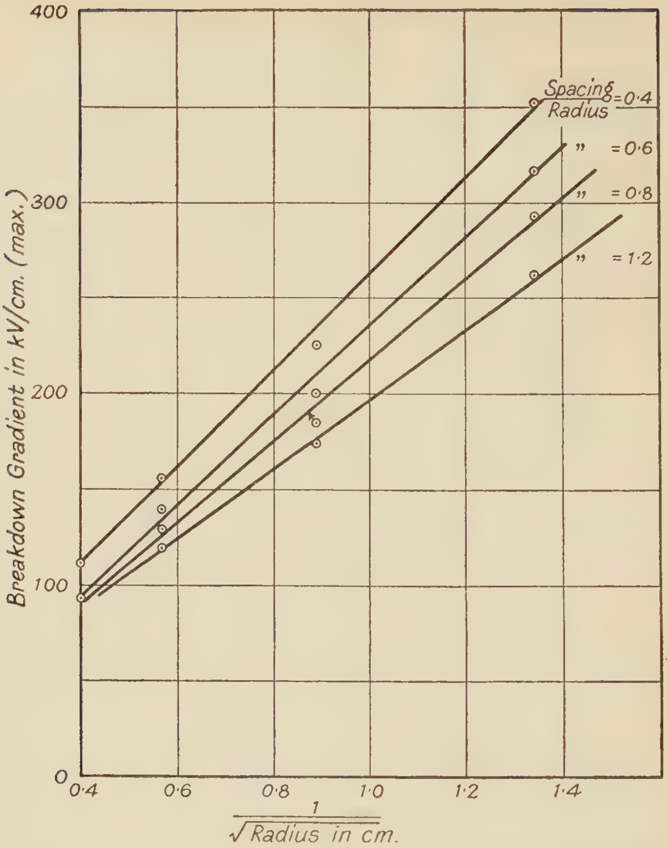

FIG. 28.—Variation of Breakdown Gradient with Radius and $\frac{\text{Spacing}}{\text{Radius}}$.

(Points from fig. 23.)

| *E.R.A.* | | *Peek* | |
|---|---|---|---|
| $\frac{x}{a}=0·2$ | $R=41·4+\frac{310}{\sqrt{a}}$ | $\frac{x}{a}=0·4$ | $R=10+\frac{251}{\sqrt{a}}$ |
| $\frac{x}{a}=0·3$ | $R=30·3+\frac{240}{\sqrt{a}}$ | $\frac{x}{a}=0·6$ | $R=1+\frac{235}{\sqrt{a}}$ |
| $\frac{x}{a}=0·4$ | $R=59·2+\frac{189}{\sqrt{a}}$ | $\frac{x}{a}=0·8$ | $R=6+\frac{210}{\sqrt{a}}$ |
| | | $\frac{x}{a}=1·2$ | $R=18+\frac{180}{\sqrt{a}}$ |

Radius $a$ is given in cm. R=kV/cm. eff.

Peek's results have been recalculated from those given in his book on the assumption that one sphere was earthed ; the actual arrangement used is not given, but one sphere earthed is the more usual. The constants A and B would agree better with the E.R.A. values if the arrangement with both spheres insulated had been used, but the general law *b*4 will remain true with either arrangement. At present, owing to the variation of quality in oils, we cannot compare the absolute values of different experimenters with any confidence. Some E.R.A. tests suggest a straight line voltage/spacing law for hexane, but the percentage variations for individual readings appear to have been large and the evidence is scanty.

### 3. VERTICAL AND HORIZONTAL ARRANGEMENT

It has often been stated that there is a marked difference between results when the sphere gap is used vertically and when it is used horizontally, owing to the greater circulation in the latter case. According to Flight,[1] if impurities are present the horizontal gap should give lower readings at small spacings where bridges may easily form and a large quantity of oil flows past the gap, but higher readings at large spacings where bridges may be dispersed. For pure oil there should not be much difference, and the tests for the E.R.A. confirm this. In the case of the latter tests the horizontal gap seems to give an anomalous minimum of breakdown gradient at small spacings. This may be compared with the anomalous minimum found by Spath [2] with uniform fields in impure oil. At higher spacings the E.R.A. results appear generally to agree better with other experimenters.

### 4. EFFECTIVE UNIFORM FIELD

With spheres in air, if the ratio of spacing to radius is less than about 0·2 or 0·3, the arrangement acts as a uniform field. It is difficult to say how far this applies to oil, as few experimental comparisons between the sphere gap and uniform field have been made on the same oil. In the case of air the uniform field extends roughly up to where the minimum of the sparkover gradient occurs. Since this minimum (if it occurs) seems to be at higher spacings in oil than in air, the effective uniform field probably extends further also. According to Peek,[1] oil has a longer energy distance than air, which implies that the effective uniform field should, for the sphere gap, extend to higher spacings, since it would follow that when the gap does not exceed the normal energy distance the field is effectively uniform.

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[1] Flight, *Electrician*, 1918, and *B.E.A.M.A. Journal* (1921).

[2] Spath, *Archiv für Elektrotechnik* (30th June 1923).

## (ii) *Impure Liquids*

### 1. SENSITIVENESS TO IMPURITIES

The sphere gap is very sensitive to impurities, as may be seen from the following table of results :—

| Investigator. | ½-in. Diameter Spheres 0·15-in. Gap kV. R.M.S. | ½-in. Diameter Discs 0·15-in. Gap kV. R.M.S. | Needles 0·15-in. Gap kV. R.M.S. | Needle and Plate 0·15-in. Gap kV. R.M.S. |
|---|---|---|---|---|
| Tobey[2] . . . | — | — | 18 | 16·5 |
| Digby and Mellis[3] . | 11·5 | — | 17·5 | 11 |
| American National Electric Light Association. Transformer Standard[4] . | 40 | 29 | — | — |
| Peek[5] . . . | 64 | 31 | 22 | — |
| Hirobe[6] . . . | 92 | 62 | — | 15 |
| Everest . . . | 20 | 20 | 22 | 18·5 |

Figures in a horizontal row refer to a given oil, so that it can be seen that a much larger variation of B.D.V. occurs with the sphere gap for differences in the quality of oil tested than for the same oils tested on other gaps. A recent article by Schwaiger[1] gives results showing clearly that the sphere gap is slightly more sensitive to impurities than the disc gap, and very much more sensitive than the gap between a sharp edge and a plane.

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[1] Peek, *Dielectric Phenomena*, p. 155.

[2] Tobey, *A.I.E.E.*, **29** (1910).

[3] Digby and Mellis, *J.I.E.E.*, **45** (1910).

[4] Report of Electrical Apparatus Committee of N.E.L.A. (June 1917).

[5] Peek, *General Electric Review* (August 1915).

[6] Hirobe, Report 25, section iii, Electrotechnical Laboratory, Tokio.

## 2. VOLTAGE/SPACING CURVES

Some curves of voltage against spacing for oils of different purities and with spheres of different diameters are shown in figs. 29 and 30. In fig. 30 it may be observed that the characteristics of impure oils are nearly straight lines, while those of pure oils show a definite curvature, but in fig. 30 only small spacings are considered. In fig. 29 it may be observed that these tests do not show very much difference in the curvatures of the characteristics for different qualities of oil at the smaller

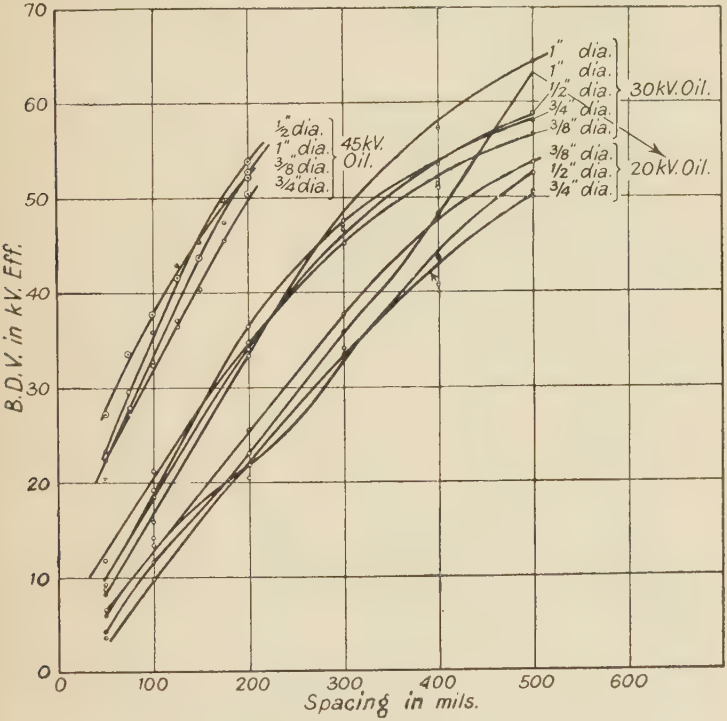

FIG. 29.—B.D.V. of Impure Oil with Spheres of different Sizes.

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[1] Schwaiger, *E.T.Z.* (10th November 1927).

spacings, the lines being nearly straight. At the higher spacings there is a more distinct curvature, which appears to occur at an earlier stage with the purer liquids. When the spacing is very large the curves for different qualities of oil must approach one another, since the gap tends to resemble the point gap, which does not show great differences between qualities of oils. This effect seems to be indicated in fig. 29.

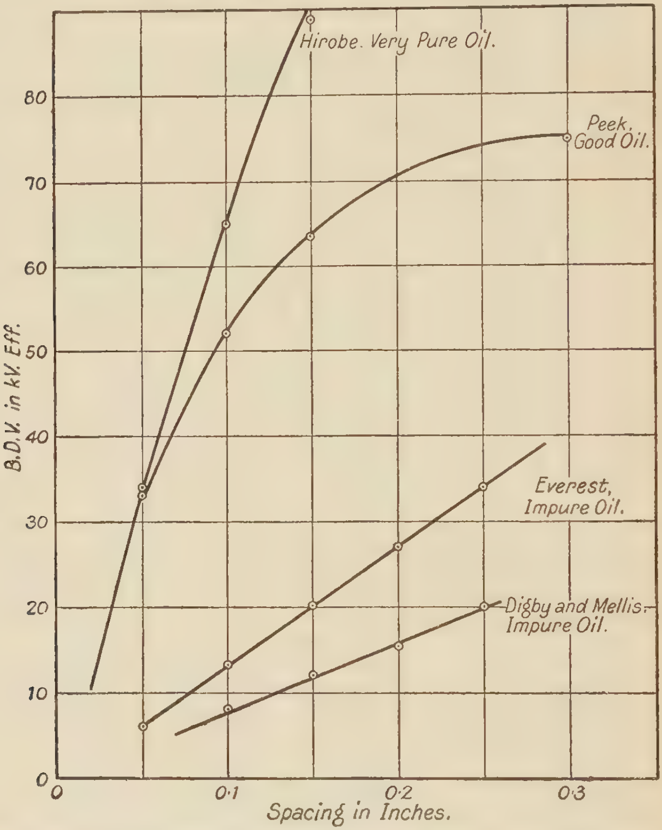

FIG. 30.—B.D.V. for ½-in. Diameter Spheres in Oils of different Purities.

When the gradient at breakdown is examined instead of the B.D.V. the curves obtained are quite anomalous, showing none of the regularities observed with pure liquids. The curves obtained with extreme values of the B.D.V. are similar to the curves of mean B.D.V. In fact, it is sometimes possible to draw a series of curves of similar shape covering an area round the mean curve on which all the individual readings lie. The liquid thus behaves like a mixture of different liquids. More probably it may be explained by the fact that the mechanism of breakdown is more or less the same but the impurities are of different kinds.

### 3. EFFECT OF DIAMETER OF SPHERE

The B.D.V. for a given gap length decreases on the whole as the diameter of the spheres increases, owing to the greater volume stressed (as found by the E.R.A.). This decrease is, however, uncertain, and the results in the tests mentioned show irregular variations. The voltage/spacing curves for larger spheres in impure oils are not usually as smooth as those for smaller spheres. The decrease of B.D.V., with increasing diameter of electrodes, may be observed also in the curves given in fig. 29 if smaller spacings are considered. When the spacing becomes very large smaller spheres would act as points, and points give a higher B.D.V. in impure oils than spheres for the same gap length. Thus both for large and small spacings the B.D.V. may be expected to be less for larger spheres, but intermediately the curves may cross.

### 4. HORIZONTAL AND VERTICAL GAP

When a liquid is tested with the sphere gap, variations are usually observed according to whether the gap is arranged horizontally or vertically. In the case of pure liquids we have seen that this difference is not significant. In the case of impure oils the difference is uncertain. For oils containing fibres the horizontal gap gives much lower values than the vertical, as may be seen in fig. 31. This is believed to be due largely to the influence of the earth plate, the effect of which is greater in the case of the horizontal than the vertical gap. With the latter the force on the fibres, which is generally from the H.T. electrode to earth, tends to remove the fibres permanently from the gap; in the former case a circulation of fibres through the gap is induced. When a good oil is contaminated with water the opposite is frequently the case, and, according to results communicated by Everest, the B.D.V. is higher on the horizontal gap. The difference is more marked if the oil is allowed to stand and the moisture to settle; the difference also decreases with increasing purity.

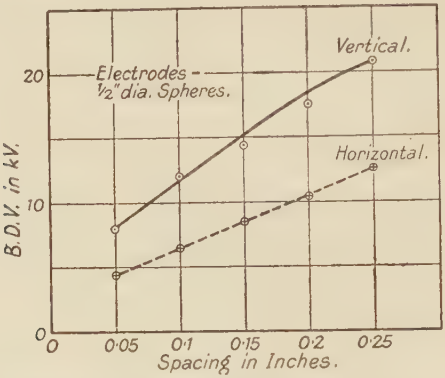

Fig. 31.—Comparison of Horizontal and Vertical Gap in testing Oil contaminated with Sawdust Fibres.

In the following table are given some results from different authorities, illustrating the features mentioned.

*B.D.V. in kV between ½-in. diameter spheres at* 0·15-*in. spacing.*

| Quality of Oil. | Horizontal. | Vertical. | Author. |
|---|---|---|---|
| Moist oil—poor . . | 20·6 | 17·6 | Everest |
| ,, —bad . . | 16·2 | 13·3 | ,, |
| Bad oil, probably fibrous . . . | 15·0 | 24·3 | Flight |
| Very bad oil containing sawdust fibres . . | 8·5 | 14·4 | ,, |
| Very good oil . . | 52·5 | 54·5 | ,, |

An investigation was carried out by the E.R.A., in which a large number of readings was taken with each of a set of different oils. It was found that the difference between the mean B.D.V.'s on the horizontal and vertical gaps was marked but inconsistent, even in the case of low-purity oils (giving 12–20 kV on the standard gap). This observation contradicted some of the previous results on low purity oils. The range of variation of individual shots was large, and the general conclusion appeared to be that the difference between the two arrangements is negligible for good oils, but may be important with low-purity oils, although in the latter case this difference cannot be said to be a property of low purity oils in general. In B.S.S. No. 148 it is concluded that "it has frequently been observed when testing poor oils that there is a difference depending on whether the common axis of the electrodes is arranged horizontally or vertically. When testing oils of the purity referred to in this specification (*i.e.* 30 kV and above on the standard gap), the difference is negligible." The standard gap is horizontal. The vertical gap has the advantage that the field is less disturbed by the earth plate, and that flashover to the earth plate is less liable to occur, but this advantage is not, however, of moment with well-designed gaps, and an oil cell with a vertical gap presents much greater constructional difficulties.

### 5. VARIATION OF INDIVIDUAL READINGS FROM THE MEAN

The sensitivity of the sphere gap to impurities is also displayed in the large variations of individual shots from the mean. These variations are on the whole larger as the sphere radius increases. For large spacings the variation eventually decreases, since the intensity of the field in approaching to that between points will also resemble the latter in relative regularity of readings. The divergence of results is greater with shorter time breakdowns up to a limit, but impulse breakdowns show a much greater regularity (see Chapter IV (*d*)). It is also observed that minima of relative variation are found at particular spacings with a given sphere radius and liquid of given quality. This may be due to some critical condition for the stability or instability of chains or bridges of impurities. The spacings at which these minima occur are, however, irregular, varying with the quality of the liquid and the size of the sphere in a complicated fashion, and it is difficult at present to draw any definite conclusions.

### (iii) *Effect of Proximity of Neighbouring Objects*

The electrostatic field in a spark gap will be distorted if conducting objects or bodies of specific inductive capacity differing from that of the ambient medium are too close. Some tests on such effects were carried out for the E.R.A., using a standard gap. When glass tubes of different diameters were fitted over the gap, it was found that thin tubes had no appreciable effect; for thick glass tubes the B.D.V. with the larger tubes was smaller than for the lesser diameters. This indicates that any restriction of circulation can have but little effect. It was also found that the nature of the glass made a difference. A metal disc behind an electrode caused a difference between individual shots rather than between means—no definite average effects were observed. It appears from these experiments that an oil gap is not very sensitive to distortion caused by neighbouring bodies of the nature tested.

Other tests seemed to show that the size of the glass container does not exert any considerable effect if the walls are further than 1 in. from the ½-in. electrodes. Miner[1] finds that sharp points near the electrodes have a considerable effect upon the B.D.V. at large spacings, and recommends that no metal parts should be near the gap with curvatures less than that of the main electrodes.

### (c) CONCENTRIC CYLINDERS

The concentric cylinder gap as generally used in actual experiments on oil has been made of such dimensions that the field has been practically uniform. The A.S.E.A. gap is of such a type, and some of its features will be mentioned here. Owing to the fact that all the impurities present are in the field, the B.D.V. on this gap is lower than for fairly uniform fields, such as with spheres, discs, or electrodes where the effective area is small and where circulation is permitted. With better quality oils, where a large variation is found with spheres, the variation with the cylinder gap is much smaller, as might be expected. The discrimination between different qualities of oil is not so great as with spheres, but greater than for needles or point and plate.

Peek[2] has examined the effect of the curvature of the inner cylinder upon the breakdown gradient and finds, for mean values

[1] Miner, *J.A.I.E.E.* (April 1927).

[2] Peek, *Dielectric Phenomena*, p. 156.

with oil, that the surface gradient R obeys a law similar to that for gas discharges, viz.:

$$R = A + \frac{B}{\sqrt{a}} \qquad . \quad . \quad . \quad . \quad 65$$

A and B are constants and $a$ = radius (see fig. 32).

This does not hold very well for small values of the radius, for the gradient becomes too high. Peek does not give details as to the quality of the oil used, or the variation of individual readings, so that from his work alone it is difficult to draw definite conclusions. Wellauer's [1] results agree with the formula to some extent. Friese [2] has suggested the use of the concentric cylinder gap in testing oil on account of the simplicity of the field and the shielding from external fields. He has been able to obtain high breakdown strengths with it in carefully purified oil. Dieterle [3] mentions the concentric cylinder gap for testing electric strength, but only gives results for filling compound.

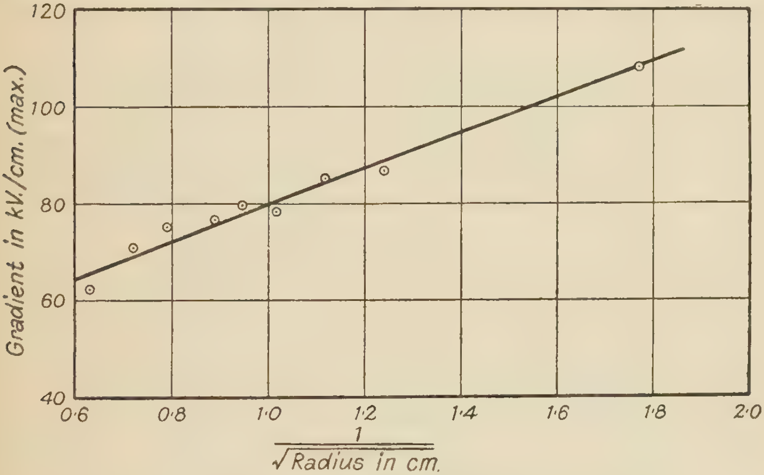

FIG. 32.—Variation of Breakdown Gradient with Radius of Inner Cylinder, according to Peek.

It would be of interest to know whether the B.D.V. varied with the length of the cylinders, *i.e.* with the electrode area. If a liquid could be obtained on which this had no effect, then investigations upon the concentric cylinder gap would give valuable information both as to the laws of breakdown for cylinders and as to those for a uniform field ; since the cylinders could easily be made so that the ratio of their diameters was nearly unity. It has not yet been shown, although Peek seems to suggest it, that the breakdown strength of liquids between concentric cylinders can be independent of the radius of the outer cylinder as is the case in air when the ratio of the radii is sufficiently large.

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[1] Wellauer, *Schweiz. Elektrotechnischer Verein* (April 1925).

[2] Friese, *Siemens Science Journal* (March 1922).

[3] Dieterle, *E.T.Z.* (May 1924).

### (*d*) POINTS

#### (i) *General Features*

The mean B.D.V./spacing curves for points, generally standard needles, usually show a fairly large curvature at small spacings, after which the curve is practically straight (see fig. 33). With

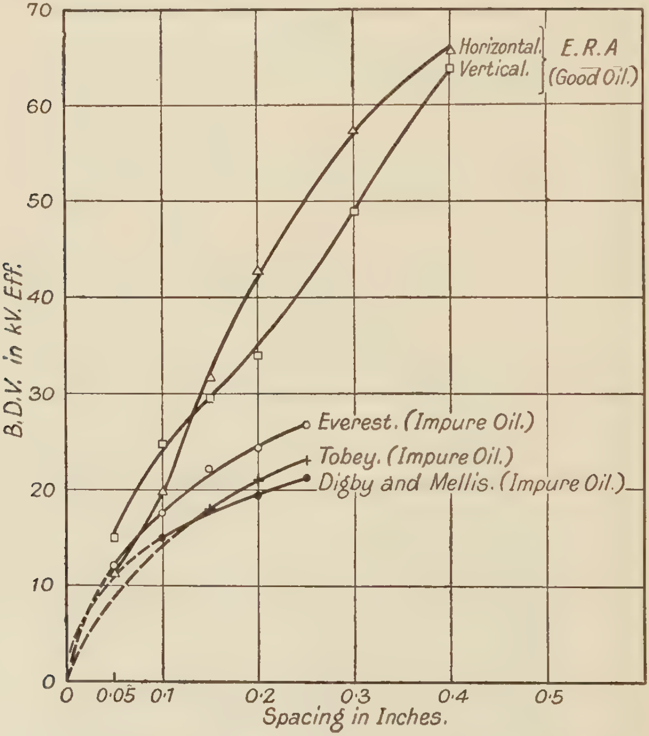

FIG. 33.—B.D.V./Spacing Curves for Oils of different Purities between Needle Points.

needle points there is much less variation between individual readings than for a uniform field, a sphere gap, or any gap where the field is more uniform and the electrodes larger. Nor do the results on different qualities of the same (or very similar) liquids, such as oils, show so much variation between one another as with other types of electrodes. The needle gap is a poor discriminator (see Table in I (*b*) (ii) 1). On the other hand, Sorge [1] has shown that results show considerable variation with difference in actual chemical constitution.

### (ii) *Pure Liquids*

With pure liquids the voltage/gap length curves are of the same general form as described above. The B.D.V. with the needle gap is always lower than with uniform field spheres and discs (see fig. 34). The percentage variation of individual readings is also less than for other gaps.[2]

### (iii) *Impure Liquids*

With contaminated liquids, for smaller spacings points give higher B.D.V.'s than spheres or discs. The difference becomes less as the spacing increases, and at large spacings the B.D.V. for points is lower than that for spheres and discs.[2] The B.D.V./spacing curve is of the same general shape as for purer liquids, but the B.D.V. is less, the decrease due to impurity increasing with the spacing (see fig. 33 and fig. 35 for large spacings).

According to Hirobe [3] these higher B.D.V.'s with impure oil on a needle gap as compared with a sphere gap are due to the instability of bridges owing to the non-uniform character of the field. The configuration of the latter would lead to a concentration of impurities in the neighbourhood of the point, and might increase the effective radius of curvature of the electrode, and so increase the breakdown voltage above the value for a pure liquid. This phenomenon has been observed in some cases. Generally, however, an oil which gives a much lower B.D.V. with spheres or discs also gives lower B.D.V.'s with needles,

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[1] Sorge, *Archiv für Elektrotechnik* (1924).

[2] Everest, *Electrician* (2nd December 1921).

[3] Hirobe, Report 25, section iii, Electrotechnical Laboratory, Tokio.

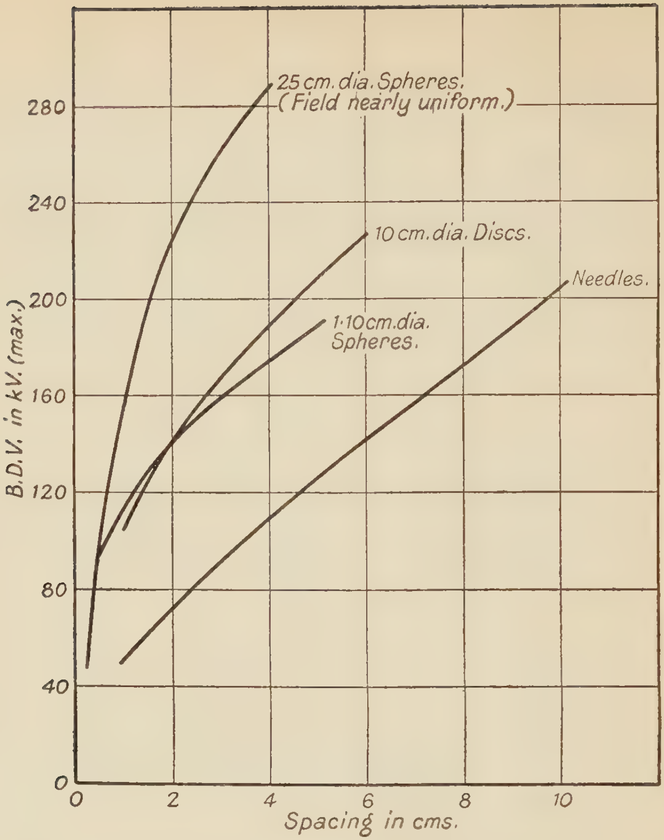

FIG. 34.—Comparison of B.D.V. with Needles, Spheres, Discs, and Uniform Field (Peek).

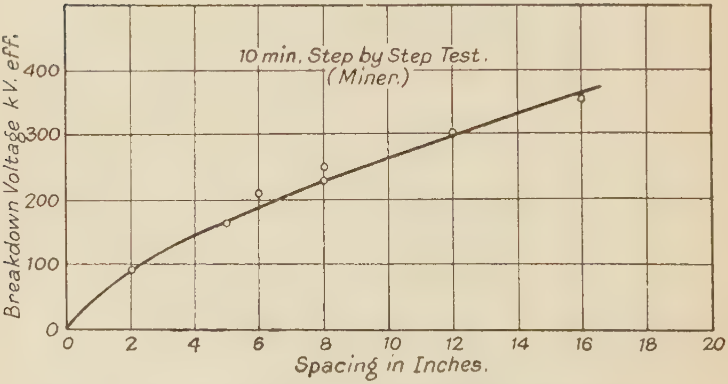

FIG. 35.—Breakdown of Oil (commercially pure) between Points.

although the difference is much less and may be imperceptible. On account of the instability of bridges many think that the breakdown values with needles are characteristic of the homogeneous liquid ; we have no means at present of proving this. The fact that needles give lower values of B.D.V. than spheres at larger spacings may thus be due either to the non-uniformity of the sphere-gap field at large spacings or to the natural variation of B.D.V. with the field of the needles themselves. The latter theory is more probable, since at higher spacings points appear to give a lower B.D.V. than uniform fields, and the latter fields do not themselves change in form with spacing.

Sorge [1] is inclined to treat points as spheres of very small radius. This is possible with the electrodes he used, but in practice the points of the needles used are not nearly regular enough. Sorge does not give the solution of the sphere-gap field by means of which he calculated the gradient. For moderately good oils Miner [2] gives the formula

$$V = A \log \frac{S}{a} \quad . \quad . \quad . \quad . \quad b6$$

as an average for long time tests (see Chapter IV). V=B.D.V., S=spacing, A and $a$ are constants.

### (iv) *Horizontal and Vertical Gaps*

It has been suggested that there should be a significant difference between the gaps when used vertically and when used horizontally, owing to the greater circulation in the latter case. It appears, however, that distortion of the field, due to surrounding earthed bodies, is a more important factor. In fig. 33 results are shown of E.R.A. investigations on the subject, from which it is seen that the difference between the two cases is insignificant.

## (*e*) POINT AND PLATE

### (i) *General Features*

The arrangement of a point opposite a plate was frequently used for oil testing in earlier years, but has been discarded in more recent times.

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[1] Sorge, *Archiv für Elektrotechnik* (1924).

[2] Miner, *J.A.I.E.E.* (April 1927).

The B.D.V./spacing curves are similar in shape to those for the needle gap. They show curvature at the lower spacings, and then tend to a straight line for larger spacings (see fig. 36). The percentage variation between individual readings is slightly larger than for the needle gap. The point and plate gap discriminates between different qualities of oils to a slightly better degree than the needle gap.

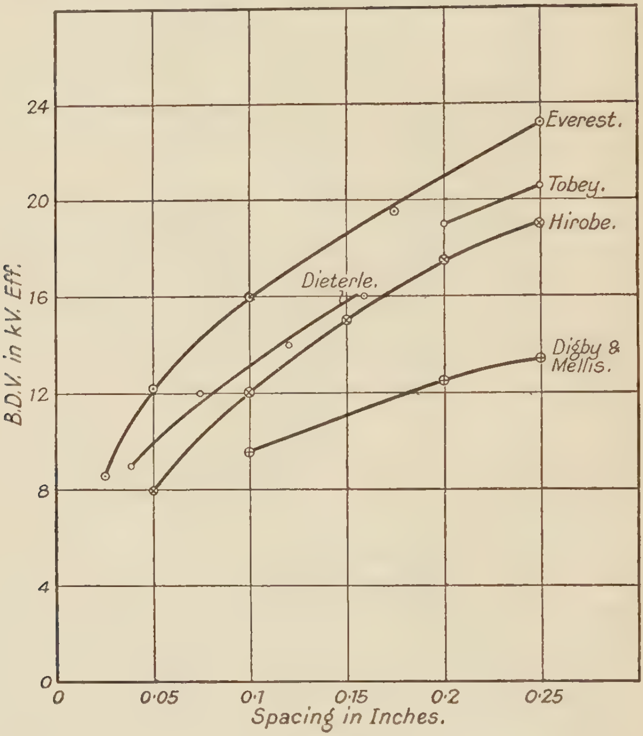

Fig. 36.—B.D.V./Spacing Curves for Insulating Oils in Point and Plate Gap.

### (ii) *Pure Liquids*

With pure liquids the B.D.V. is lower when the point and plate gap is used than with spheres and discs. It is not very different from that with the needle gap. From the similarity of the electric field one might expect that the B.D.V. on a given point and plate gap would be half that on a needle gap twice as long. If breakdown in liquids is similar to that in air, of course the supposition would be untrue, as half the ionisation would be cut off in the case of the point and plate gap, and the amount of ionisation necessary for the discharge is not proportional to the voltage. There is, however, some indication that such a relation might hold in a few cases, but comparisons are uncertain owing to variations in the liquids and irregularity of readings.

### (iii) *Impure Liquids*

With impure liquids the point and disc gap gives results fairly similar to those with needle points, but on the whole the B.D.V. for the latter is lower than for the former, particularly at larger spacings.[1] The point and plate B.D.V. is greater than the B.D.V. with spheres and discs, except at the higher spacings where the latter exceeds the former. There is no relation between the point and plate gap and the needle gap for bad oils analogous to the relation between their electrostatic fields. The B.D.V. on the point and plate gap is relatively much too high. The point and plate gap is to some extent intermediate between the disc and needle gaps, but more nearly resembles the latter in its general properties.

## (*f*) Discs

### (i) *Introductory*

The discs used in investigations on liquids are circular flat plates with rounded edges. The field in the centre is more or less uniform, becoming weaker towards the circumference, but with a concentration of flux at the edges. On this account the field between two discs has been compared with that of a sphere gap having a needle gap in parallel.[2] The gap is used in America as a standard for oil testing.

### (ii) *Pure Liquids*

With good oils (oils only have been extensively tested in this gap) the B.D.V./spacing curves are of the same shape as for spheres, but the values are lower (see figs. 34, 37, and 38). The curves for spheres, uniform fields and discs seem, according to Hirobe,[1] to superpose for the lower spacings. Tests made for the E.R.A. do not show this. With a pure liquid the effect is not to be expected, since, with a homogeneous fluid, breakdown would probably occur at the edges rather than where the field is uniform. It has often been observed experimentally that the purer the oil the fewer breakdowns there are in the middle of the disc, although this is not always the case. With pure oil the mean curves for discs give higher B.D.V.'s than for needles or point and plate, but lower B.D.V.'s than for spheres or uniform fields. Even if the highest individual readings are taken the gap between discs breaks down at a lower voltage than the gap between spheres of any size, and it seems therefore that the edge effect has some influence. The variation of individual readings

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[1] Everest, *Electrician* (2nd December 1921).

[2] Flight, *B.E.A.M.A. Journal* (February–March 1921).

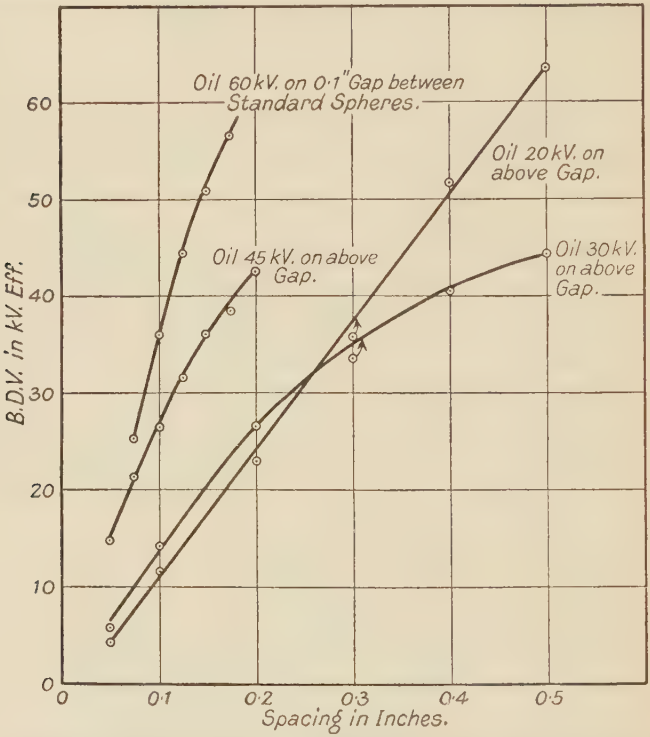

FIG. 37.—B.D.V./Spacing Curves for Gap between 1-in. Diameter Discs.

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[1] Hirobe, Report 25, section iii, Electrotechnical Laboratory, Tokio.

from the mean is of the same order as for spheres, and decreases as the gap length is increased (see Wellauer[1]).

### (iii) *Impure Liquids*

As oil becomes more and more impure the B.D.V. for a given setting with discs has been found (as in E.R.A. work) to approach closer and closer to that for spheres. At the smaller spacings this is especially marked, and it has also been observed that with decreasing strength of oil (*i.e.* the less pure the oil) the rapidity of the approach increases as larger discs are used. With impure oil the breakdowns largely take place near the centre of the discs, and not so much at the edge as is the case with purer oil, and the variation of individual readings is not very different

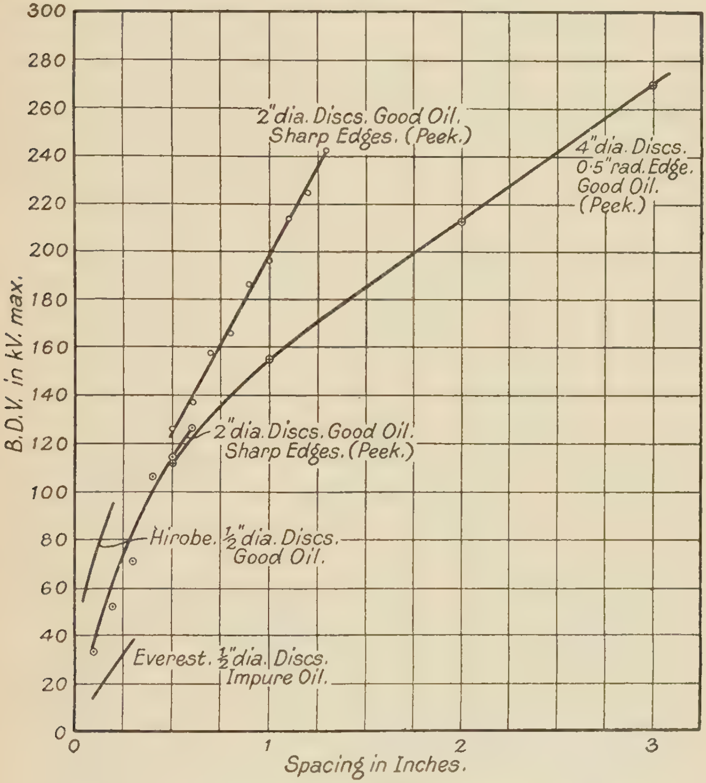

FIG. 38.—B.D.V./Spacing Curves for Gap between two Discs.

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[1] Wellauer, *Schweiz. Elektrotechnischer Verein* (April 1925).

from that with the sphere gap. Wellauer,[1] however, finds a sudden decrease in the electric strength at small spacings.

The above may be simply explained if we consider the breakdown as due to strings and bridges. As these strings and bridges are unstable in a distorted field, the effect of flux concentration at the edge of the field will be small. The uniform part of the field, which is similar, at small spacings, to that of the sphere gap, will be most important, and so the B.D.V.'s for spheres and discs will approach each other. The larger the disc the less is the effect of the edge, for the area increases more rapidly than

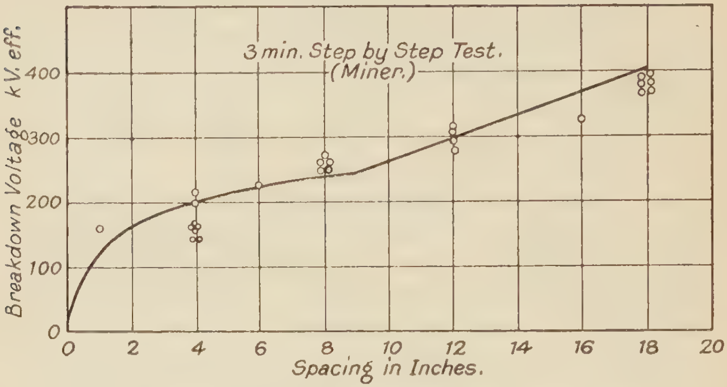

FIG. 39.—Breakdown of Oil (commercial pure Transil) between ½-in. Diameter Rods.

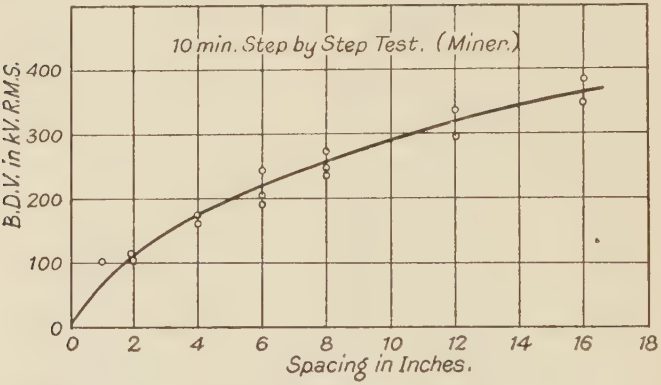

FIG. 40.—Breakdown of Good Oil between 1-in. Diameter Rods.

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[1] Wellauer, *Schweiz. Elektrotechnischer Verein* (April 1925).

the circumference, and so the resemblance to the sphere gap will be closer. With impure oils the disc gap acts as a uniform field. With fairly pure oil Miner (*loc. cit.*) has found anomalous variations in the voltage/spacing curve for discs (fig. 39), but regularity was obtained with a longer time of test (fig. 40).

### (iv) *Variation of B.D.V. with Area of Disc*

As the area of the disc is increased the probability of a stray impurity or chain of impurities causing breakdown increases, while the mean B.D.V. also decreases. Miner[1] gives the following formula for the average B.D.V. of fairly good oil,

$$V = Ad^m \log \frac{S}{Bd^n} \quad . \quad . \quad . \quad . \quad 67$$

where V=B.D.V., $d$=diameter of disc, S=spacing, A, B, $m$, $n$ are constants. This is on the basis of his three-minute step-by-step test.

Fig. 41 shows some curves by Farmer[2] illustrating this effect. The strength falls rapidly as the area increases, tending asymptotically to a constant value. The variation of strength with area differs according to the gap length used; for the longest gap the variation is small, the strength being practically independent of area, but there does not appear to be a regular variation in the final constant minimum values with gap length, although the initial readings are in right order. We should not, however, for a long gap expect much variation, since bridges and chains would be unstable. Farmer[2] does not say whether he used the same oil in each set of tests, nor does he describe the oils used, so that his results can only be interpreted qualitatively. The application of probability considerations to this effect will be considered in Chapter VIII.

### (v) *Variations from the Mean*

It may be observed that, as with spheres, a pronounced minimum in the deviation of individual readings is often found at a particular spacing for a given set of tests. This is more frequently observed with purer oils, the less pure giving more

[1] Miner, *J.A.I.E.E.* (April 1927).

[2] Farmer, *J.A.I.E.E.* (1913).

regular results. The effect appears to vary with all the conditions of a given set of experiments. The divergence also appears to decrease as the length of the gap increases. This, according to Wellauer, is particularly noticeable at small spacings.

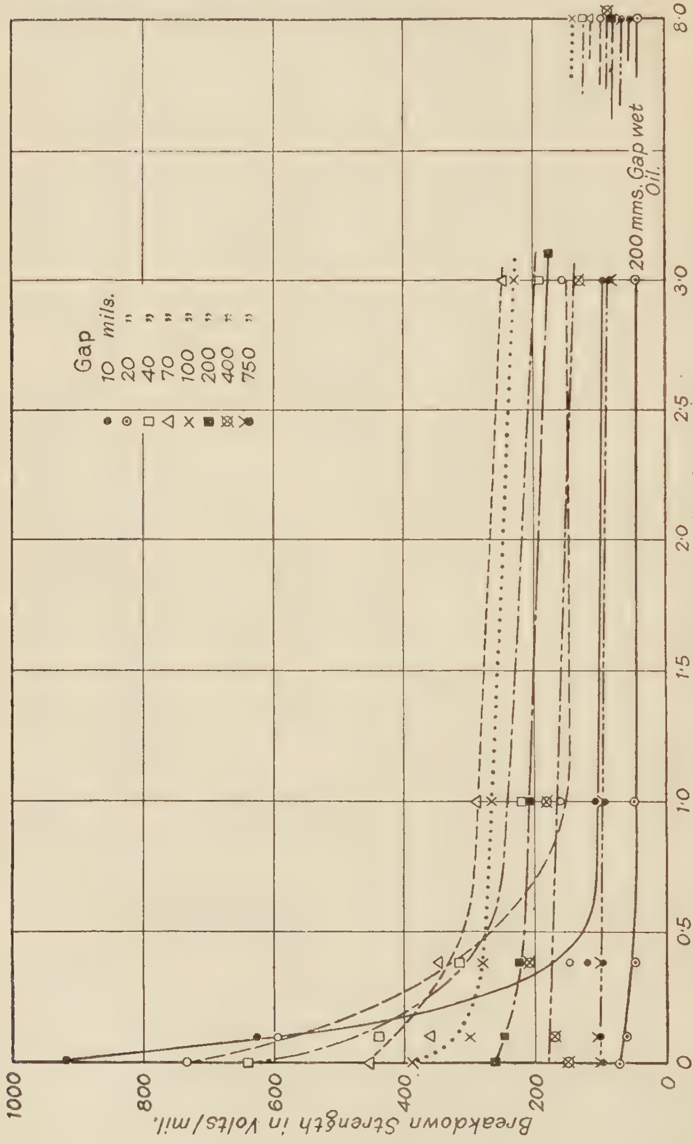

Fig. 41.—Effect of Disc Area upon B.D.V. (Farmer).

### (vi) *Horizontal and Vertical Gap*

Tests were carried out for the E.R.A. to discover whether any important difference arises when the gap is used horizontally or vertically. Some results are shown in fig. 42, and in general it was found that, although such a difference does occur, it is variable and not significant, particularly when a large number of readings are taken, and with high purity liquids. Contaminated liquids show irregular variations. The same considerations on this matter in the case of the sphere gap apply also to the disc gap.

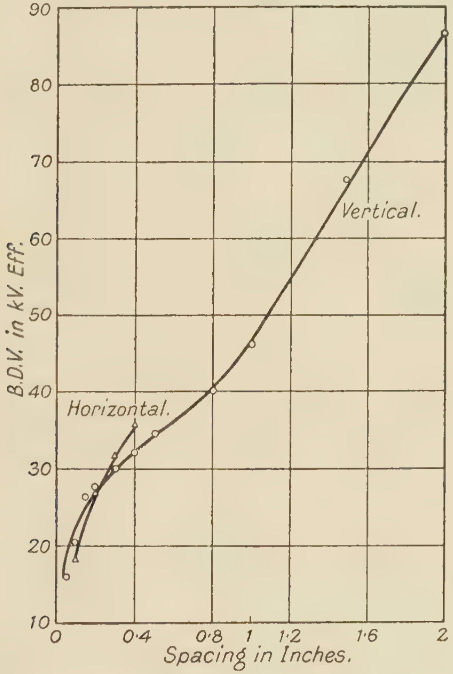

FIG. 42.—Horizontal and Vertical Disc Gap. 1-in. Diameter Discs.

### (*g*) CONCENTRIC SPHERES

This form of electrode is only mentioned for completeness, as no investigations have been made upon it. It has been proposed by Dieterle[1] as a standard gap on the grounds that the field is simple in form and shielded from external fields. The filling and emptying of such a gap might prove difficult, and such an arrangement is not likely to give such good discrimination as spheres or discs, owing to the large volume of liquid tested and the lack of circulation.

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[1] Dieterle, *E.T.Z.* (May 1924).

### (*h*) Co-axial Cones

This form of gap has also been proposed by Dieterle as giving a simple and nearly uniform field. It would be easier to fill with liquid than the concentric sphere gap, and would be equally independent of external fields. Some figures are given by Dieterle [1] for oil (see fig. 43), and it appears that there is very wide divergence between individual readings. He does not, however, give details as to the nature of the oil tested. There is a possibility of flux concentration at the rims of the cones, and such a gap would give low values even with very good oils, owing to the lack of circulation.

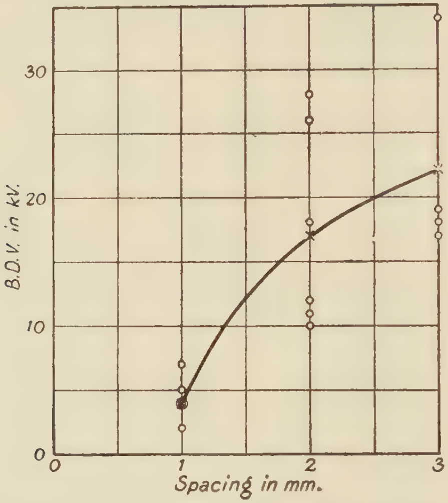

Fig. 43.—Breakdown Voltages for Co-axial Cones in Oil (Dieterle).

### (*j*) Polarity Effects

Using unsymmetrical electrodes in air it is found that the breakdown voltage varies with sense of the applied voltage owing to the difference between the ionising efficiencies of the positive and negative ions. Spath[1] has observed a similar effect with oil using electrodes of different sizes. He found that the B.D.V. when the smaller electrode was negative was about half as much again as when the smaller electrode was positive. An influence machine was used and the gap ionised with ultra-violet light.

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[1] Dieterle, *E.T.Z.* (May 1924).

Sorge[2] found a small polarity effect with transformer oil, but none with hexane. As his gap was almost symmetrical no polarity effect was to be expected.

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[1] Spath, *Archiv für Elektrotechnik* (30th June 1923).

[2] Sorge, *Archiv für Elektrotechnik* (1924).

# CHAPTER III

## THE EFFECT OF TEMPERATURE AND PRESSURE

### (*a*) Effect of Temperature

### (i) *General Features*

In the case of average commercial insulating oils the B.D.V. increases as the temperature rises. For an impure oil this increase appears to continue up to temperatures near the boiling-point of the oil. If a medium quality oil is heated and then cooled the descending B.D.V./temperature curve is higher than the ascending B.D.V./temperature curve. In most cases with oil of good commercial quality a maximum in the B.D.V. is observed with temperature. The B.D.V. increases up to a temperature of between 60° and 80° C., subsequently decreasing. Flight [1] gives 80° C. for the maximum B.D.V., using good commercial oil with a vertical gap. Peek [2] gives the maximum round about 95° C. for one set of experiments, for another he gives 80° C. for high quality oil (subsequent cooling in this case had practically no effect on the B.D.V.). Friese,[3] using a very good oil, gives a maximum at 60° or 70° C. Sorge,[4] also using well-purified oil, gives a maximum at 65° C. Butman [5] gives a constant maximum for pure paraffin oil extending from 50° to 100° C. for a large gap, but a single peak at 50° C. on a small gap. Spath [6] gives a maximum at 65° C. Butman [5] finds that the B.D.V./temperature curve for paraffin varies with gap setting; the maxima and minima, however, occur at the same temperatures. On the whole it appears that the purer the oil or the greater the elimination of the effect of impurities, *e.g.* by using a particular configuration of gap, the further the maximum of electric strength is shifted towards lower temperatures, and it also becomes less pronounced.

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[1] Flight, *B.E.A.M.A. Journal* (February–March 1921).

[2] Peek, *Dielectric Phenomena*, p. 185.

[3] Friese, *Siemens Science Journal* (March 1922).

[4] Sorge, *Archiv für Elektrotechnik* (1924).

[5] Butman, *Electrical World* (26th April 1918).

[6] Spath, *Archiv für Elektrotechnik* (30th June 1923).

Hirobe,[1] for example, using very pure oil finds very little change in B.D.V. between 15° and 65° C., and we have already mentioned the constant cooling curve given by Peek [2] (see fig. 44). Hayden and Eddy [3] found that the B.D.V. of Transil oil (No. 6) decreased steadily over a range of 25° to 75° C., both for direct current and 60 ~ stresses. The decrease was more rapid with the alternating stress. This oil changes considerably in viscosity as the temperature increases, and, as will be mentioned later,

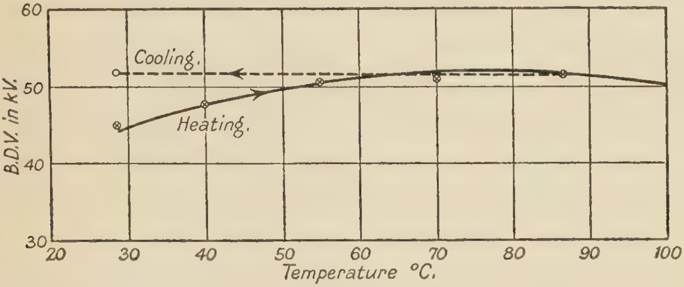

Fig. 44.—Effect of Rise and Fall of Temperature on B.D.V. of Oil (Peek) Tested between Discs.

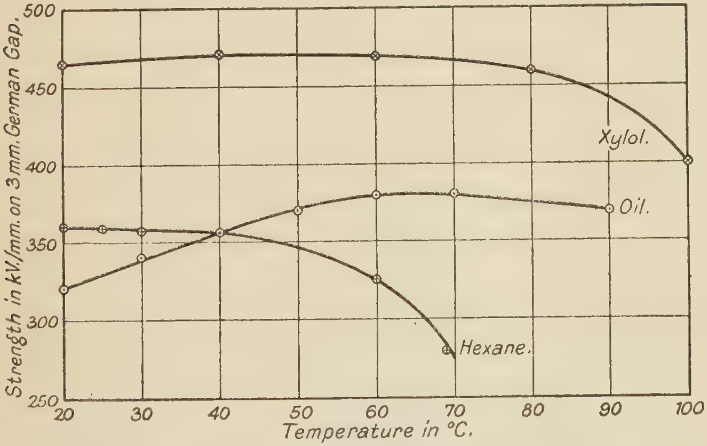

Fig. 45.—Effect of Temperature on Strength of Pure Liquids.

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[1] Hirobe, Report 25, section iii, Electrotechnical Laboratory, Tokio.

[2] Peek, *Dielectric Phenomena*, p. 185.

[3] Hayden and Eddy, *J.A.I.E.E.* (July 1923).

there is evidence that decrease in viscosity is associated with the increase of electric strength of liquids with temperature when breakdown is mainly due to impurities. There is therefore some reason for supposing that the breakdown in the experiments of Hayden and Eddy was, to a large extent, independent of impurities. When simple pure liquids are used the B.D.V., according to Sorge[1] (see fig. 45), decreases with temperature, and the fall of electric strength with temperature is characteristic of practically all insulating substances except oils or combinations including oil.

### (ii) *Variation of B.D.V. at Transition Points*

Tobey[2] early showed that there is a rapid increase of B.D.V. in the neighbourhood of the freezing-point of an oil (see fig. 46).

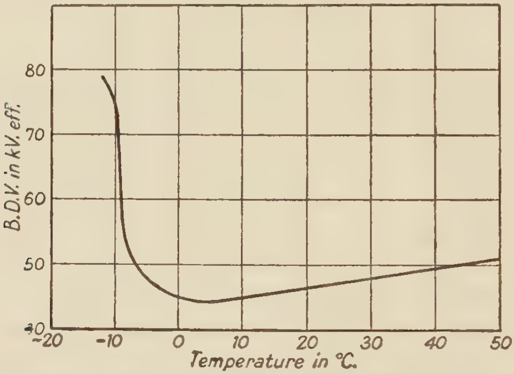

Fig. 46.—Effect of Temperature on B.D.V. of Oil in Neighbourhood of Transition Point (Tobey).

A curve given by Butman[3] also shows this (see fig. 47), and the phenomenon of the increase of the B.D.V. on freezing is generally accepted as holding in any case for oil, and probably for other insulating liquids.[4] At the upper transition point—the boiling-point—a sharp drop of B.D.V. occurs. This has been found by Sorge to hold for xylol and hexane, for oil by Butman[3] (see fig. 47), and many others. As the electric strength of the

[1] Sorge, *Archiv für Elektrotechnik* (1924).

[2] Tobey, *A.I.E.E.*, **29** (1910).

[3] Butman, *Electrical World* (26th April 1918).

[4] Peek, *Dielectric Phenomena*, ch. vi.

vapour is less than that of the liquid, a fall in the electric strength of the liquid is to be expected at the transition point.

### (iii) *Drying out of Impurities*

Originally the initial positive temperature coefficient, the maximum of B.D.V., and the higher values of B.D.V. for the cooling curve, were explained for oil by saying that moisture and similar impurities, *e.g.* dissolved gases, were dried out or driven off by the rise of temperature. Beyond a certain temperature the normal decrease of strength with temperature asserted itself, giving a maximum B.D.V., and if an oil were cooled after heating, its B.D.V. would be relatively higher owing to the fact that the reabsorption lagged behind the temperature. This theory would only apply to relatively volatile impurities, the most important being moisture. There would be no effect upon solid impurities. Again, Peek [1] obtained the positive temperature coefficient and maximum of B.D.V. with oil containing less than

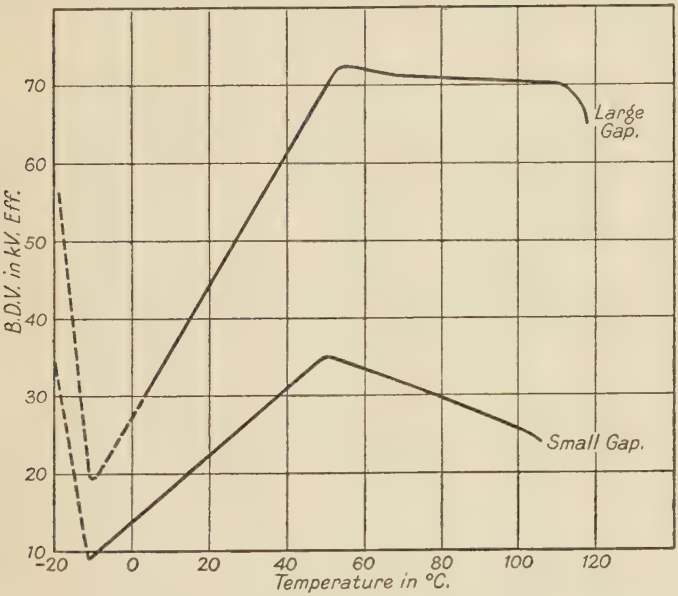

FIG. 47.—Effect of Temperature on B.D.V. of Oil (Butman).

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[1] Peek, *Dielectric Phenomena*, ch. vi.

eight parts per million of water. Many other workers (*e.g.* Peek,[1] Friese,[2] Spath,[3] Flight [4]) have obtained the effects with oil of high purity. Although the drying-out theory is not a complete explanation of temperature effects, it undoubtedly plays an important part with impure oils. Where no maximum is observed until in the neighbourhood of the boiling-point, the positive temperature coefficient is probably due to drying out. The greater the moisture content the greater the rise of B.D.V. with temperature.

### (iv) *Relation between Viscosity and Temperature Coefficient*

As the temperature of a liquid rises the viscosity decreases. This is particularly the case with insulating oils, which can be plainly observed to become thin on heating. The lower the viscosity the more rapid will be the circulation, and consequently impurities will be carried more rapidly from the field. It has been observed that the higher the viscosity of an oil the greater is the positive temperature coefficient. The lower the viscosity of an oil the higher is the electric strength (see Chapter VI). Friese [2] suggested that the increase in strength should be correlated with the decrease in viscosity, and Draeger [5] has found that there is a linear relation between the breakdown strength and the reciprocal of the viscosity. Flight [6] says that the temperature coefficient is greater with a horizontal gap than with a vertical gap, owing to the direction of circulation in the latter being at right angles to the axis of the gap (see fig. 48).

### (v) *General Considerations*

From the evidence examined it appears probable that the electric strength of pure liquids decreases with rise of temperature, as is the case with other dielectrics. On freezing the strength rises, and on boiling it falls. If, however, there are impurities present, the strength rises with temperature up to a certain point, owing partly to the removal of some of them (*e.g.* moisture), and partly to the decrease in viscosity and consequent increase in circulation causing the impurities to have less effect. At a certain temperature, generally lower the purer the liquid, the effect of impurities is so much decreased that the normal fall of the strength of the pure liquid comes into play, thus giving a maximum strength at a given temperature.

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[1] Peek, *Dielectric Phenomena*, p. 185.

[2] Friese, *Siemens Science Journal* (March 1922).

[3] Spath, *Archiv für Elektrotechnik* (30th June 1923).

[4] Flight, *J.I.E.E.*, **52**.

[5] Draeger, *Archiv für Elektrotechnik*, **12** (August 1924).

[6] Flight, *B.E.A.M.A. Journal* (February–March 1921).

The above explanation can only be regarded as tentative, since the evidence is not of a conclusive nature. In some of the tests carried out for the E.R.A., a maximum of the resistance of an oil was found at 50° C. None of the breakdown tests on similar oils showed a maximum anywhere approaching this temperature. Butman[1] finds that at the temperature where the conductivity begins to increase more rapidly the breakdown strength begins to fall, or at any rate ceases to rise. If the maximum of electric strength occurs when the impurities are at a minimum, we should expect an accompanying decrease in

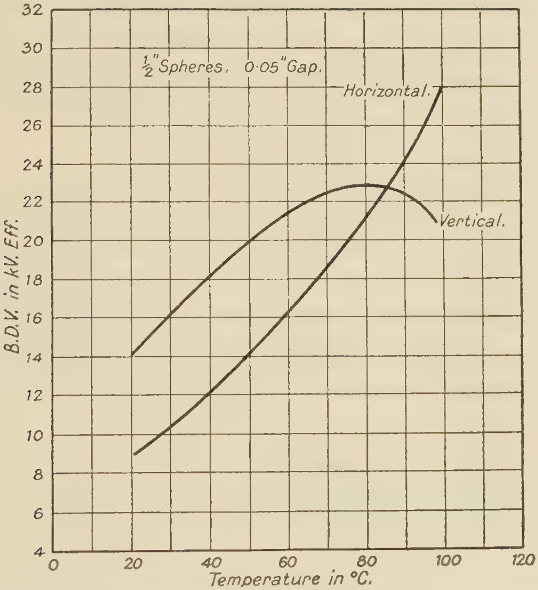

FIG. 48.—B.D.V./Temperature Curves for Horizontal and Vertical Gap.

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[1] Butman, *Electrical World* (26th April 1918).

conductivity. If, however, the main effect is regarded as due to fibre bridges and flux concentration by impurities not necessarily detrimental to the resistance, then we are considering a specific type of breakdown, and have no evidence that its importance is of such generality as the positive temperature coefficient. The effect of circulation is not altogether definite, for we might consider it as increasing effectively the volume of oil actually under test, so that it should in some cases decrease the breakdown voltage. Butman[1] has suggested that the conductivity current may " protect the polarised molecules " from breakdown, but exactly what is meant is not clear. The chief difficulty is that we cannot specify the type or types of breakdown which occur, and so hypotheses concerning the effect of temperature upon them are necessarily somewhat vague.

In conclusion, a further view may be mentioned. As the temperature rises the impurities present are more intimately dispersed in the medium, and so have less effect upon the breakdown strength. This may be due either to the intrinsic effect of heat, or to the circulation arising from lower viscosity, or perhaps partly to a lowered surface tension. After a certain point the fall with temperature of the true strength of the liquid exerts its effect. In support of this it has been found that the variation of individual readings is smaller with hot oil than with cold. Actual experimental results are probably due to the sum of the action of the various effects suggested in explanation.

### (*b*) The Effect of Pressure

The effect of pressure upon the breakdown of liquids has not been investigated to any extent, as, in practice, pressures large enough to exert an appreciable effect are exceptional. Flight[2] mentions that there is no difference in the B.D.V. whether the gap is two inches or two feet below the surface of the oil, but if nearer the surface the gap may spark over through the air. The pressure corresponding to a head of two feet of oil is, however, small. Friese,[3] using carefully dried oil, finds that the strength varies linearly with the pressure according to the formula

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[1] Butman, *Electrical World* (26th April 1918).

[2] Flight, *B.E.A.M.A. Journal* (February–March 1921).

[3] Friese, *Siemens Science Journal* (March 1922).

$$g=86+0{\cdot}08p \qquad . \quad . \quad . \quad . \quad c1$$

$g$=strength (3 mm. German gap) in kV/cm., $p$=pressure in mm.

Sorge[1] finds that similar laws hold for xylol and hexane, viz.,

$$\text{Xylol } E=159+0{\cdot}42p \qquad . \quad . \quad . \quad . \quad c2$$

$$\text{Hexane } E=144+0{\cdot}31p \text{ (see fig. 49)} \qquad . \quad . \quad c3$$

using probably a similar gap to Friese's.

This linear increase of strength with pressure is interesting from the point of view of the effect of impurities; since if fibre bridges, etc. were causing the breakdown one would not imagine pressure to have any very definite effect. It thus appears that the breakdown in the liquids examined depended in some measure on the intrinsic properties of the liquids.

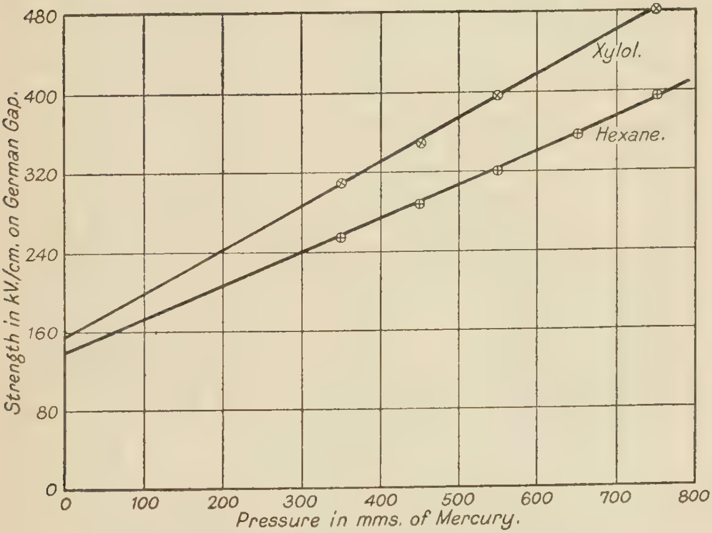

Fig. 49.—Effect of Pressure on Strength of Pure Liquids.

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[1] Sorge, *Archiv für Elektrotechnik* (1924).

# CHAPTER IV

## SPARK LAG AND ALLIED PHENOMENA

### (*a*) Introductory

With liquids, as for solid insulation and for air between needle points, a certain interval elapses between the application of the voltage and the passage of the discharge. This effect is known as " spark lag," and the interval is known as the " time lag." The effect of this may conveniently be considered from three aspects :

(1) When the time interval is long compared with the time for one cycle of the alternating voltage used, then the average stress will be the same for voltages of the same form and effective value, and a time/voltage relation may be obtained between the time of application and the magnitude of the applied voltage.

(2) It is found that the B.D.V. of liquids depends upon the frequency, and the ratio of the B.D.V. at a given frequency to the B.D.V. under direct current stress is known as the impulse ratio. In some cases the 50-cycle B.D.V. or 60-cycle B.D.V. has been taken as standard. By analogy with gases, the variation with frequency has often been thought to be due to a " time lag " of magnitude comparable with the period of alternation of the voltage. Actually, however, the variation with frequency is observed even with long time lags.

(3) When a limited short train of waves or a given impulse is applied to the gap other factors, such as wave form, become of considerable importance, and the phenomenon will be called " breakdown under transient."

### (*b*) Time/Voltage Relation

#### (i) *Experimental Results*

As the " time lag " is indefinitely reduced, the voltage necessary for breakdown appears to become indefinitely large. At any rate there appears to be no tendency to a limit for intervals down to the period of the applied voltage. As the applied voltage is decreased, the time lag increases more and more rapidly, showing the existence of a minimum voltage below which the gap will not under any circumstances break down. All time/voltage curves show these general characteristics, but in details the curves vary with other factors, chief amongst them being the amount of deleterious impurity present. With more impure oils the voltage falls off rapidly for lags of less than three or four seconds, after which the voltage curve bends sharply and decreases slowly to a limit. With purer oils, and other oils when tested hot, the decrease of voltage with increasing time lag is more gradual, the curvature being less the purer the oil.

In the case of some experiments on oil with the B.E.S.A. gap, it was found possible to express the relation as

$$V=V_0+At^{-n} \qquad . \quad . \quad . \quad . \quad d1$$

V=B.D.V. (effective), $t$=time of application, $V_0$, A, and $n$ are constants.

Fig. 50 shows four representative curves plotted on logarithmic paper to illustrate the formula. The exponent $n$ decreases as the oil becomes purer or hotter, which in many cases amounts to much the same thing, while the minimum or "infinite time" voltage, $V_0$, increases. We may compare this formula with Peek's for solid insulation,

$$V=V_0+At^{-\frac{1}{4}} \qquad . \quad . \quad . \quad . \quad d2$$

The form of the time/voltage curve also depends upon wave form. Fig. 51 shows two time/voltage curves for the same oil, an impure one, the upper obtained with an induction coil, and the lower with a transformer giving a sinusoidal wave. Maximum values of the voltages are plotted, so that the higher maximum voltage required by the induction coil may be considered as due to the higher peak factor compared with the transformer.

Time/voltage curves must also vary with the type of gap employed, although not much evidence is available on the point. Fig. 52 shows a curve given by Flight[1] for a good commercial oil where a needle gap was probably used.

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[1] Flight, *B.E.A.M.A. Journal* (February–March 1921).

Iwatake [1] considers time lags, of the order of those taking place

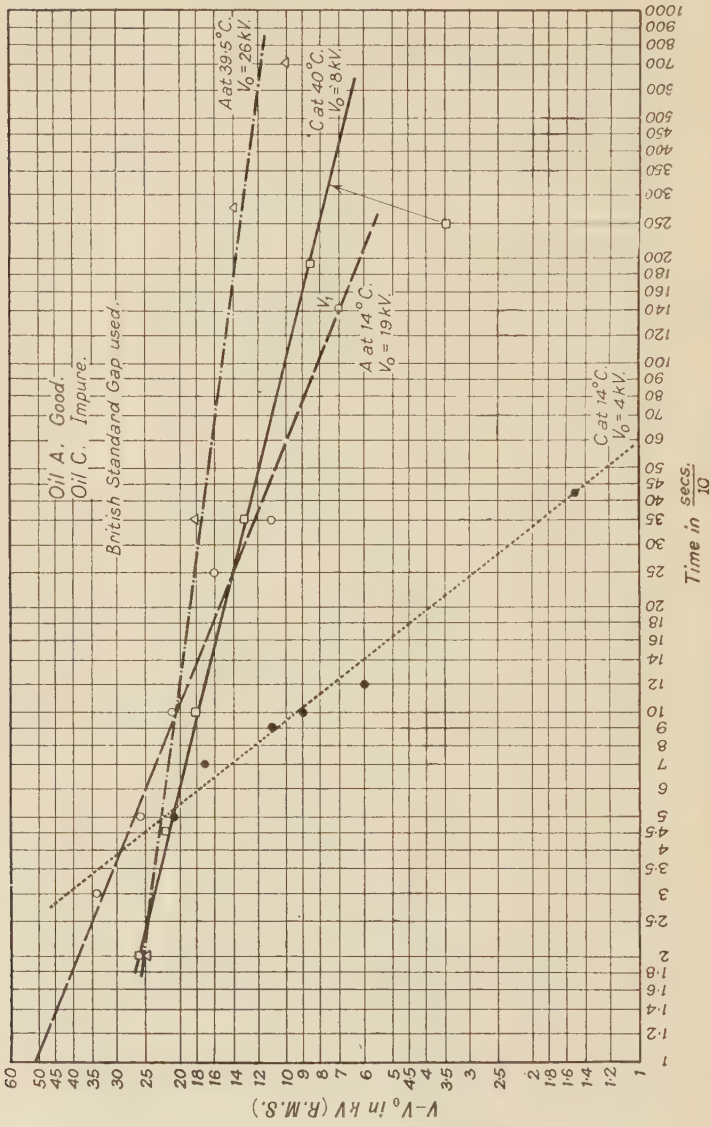

FIG. 50.—Time Voltage Curves showing Relation $V - V_o = At^m$.

in gases, occur in the case of instantaneous breakdowns in liquids. The time lag is supposed to increase with spacing.

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[1] Iwatake, *Inst. El. Eng. of Japan*, No. 446 (September 1915).

### (ii) *General Considerations*

All the evidence available is on oils of commercial purity, so that the breakdown, particularly when the long times of application are concerned, is probably due largely to impurities. The particles dispersed in the fluid move up into the gap in a time determined by their distances from the gap, their size, the viscosity of the medium, and the average value per half-cycle of the voltage. The longer the time, the more probable is the formation of a bridge or chain, so that a greater consistency of results, as well as a lower B.D.V., is to be expected. This has been observed, *e.g.* Miner [1] has shown the divergence of readings from the mean to decrease in proceeding from the instantaneous test to the three-minute and ten-minute step-by-step tests.

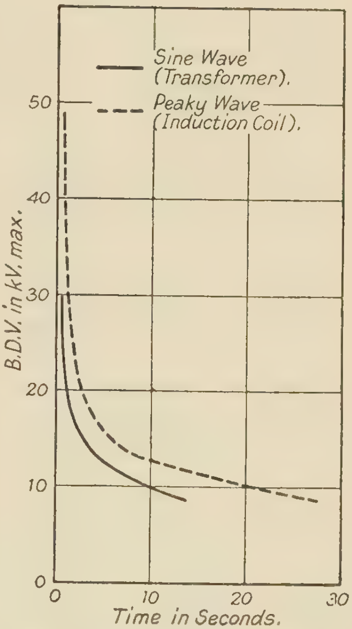

FIG. 51.—Effect of Wave Form on Time/Voltage Curve.

It has been suggested (*e.g.* Flight [2]) that the time lag may be divided into two parts: one depending upon the time for impurities to move into the gap, and the other being a characteristic of the liquid. The latter presumably refers to the lag associated with the burning out of a chain or the breakdown of the liquid in the neighbourhood. It seems that this would depend as much upon the nature of the impurities as upon the nature of the pure liquid itself. If dielectric particles of a certain class are situated at a certain mean distance from the gap, the time taken to reach the latter will be inversely proportional to the mean square voltage, since the force upon them for a given configuration of the field is

[1] Miner, *J.A.I.E.E.* (April 1927).

[2] Flight, *B.E.A.M.A. Journal* (February-March 1921).

itself proportional to the mean square voltage (see Chapter I). The time for breakdown to take place when the particles have collected and bridged the gap will depend upon either the effective or the peak voltage, but the former would probably be more important if breakdown is assumed to be analogous to the burning-out of a fuse. Thus, in such a case, the lag could perhaps be expressed as

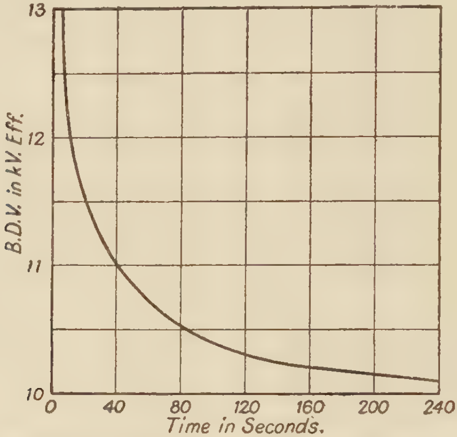

FIG. 52.—Time/Voltage Curve (Flight). Probably with Needle Gap.

$$\text{lag}=t=\frac{A}{V^2_{\text{eff}}}+f(V_{\text{eff}}) \qquad . \quad . \quad . \; d3.1$$

where A is a constant and $f(V_{\text{eff}})$ is some function of the effective voltage.

In the case of a charged particle the matter is more complicated, since the average force is zero if the particle retains its charge. Many of the particles will reach the gap before the voltage changes sign, and in other cases the magnitude of the charge will change as the particles move in the field. Information is not yet available as to the intrinsic behaviour of such impurities. According to Draeger [1] part of the time lag is accounted for by the collection and generation of ions, as in the case of air. This agrees also with Gunther Schulze's view that breakdown occurs through ionisation in vapour paths produced by rapidly moving ions. The formation of these paths would account for the lag associated with the actual breakdown, and represented by the second term in equation $d3{\cdot}1$. On such a theory the time for breakdown should increase as the spacing increases, since with the same forces the paths of ionisation would require a longer period of formation. This may account for part of the decrease of breakdown strength with spacing when liquids are tested in uniform fields and breakdown takes place after a given period of application of stress. Draeger finds that illuminating the gap with an ionising radiation reduces but does not remove the lag. Spath,[1] on the other hand, found no effect from such radiations.

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[1] Draeger, *Archiv für Elektrotechnik*, 12 (August 1924).

### (iii) *Heating Effects*

It is assumed in the above that no appreciable general heating of the liquid takes place through dielectric losses. This is generally the case since the power factors of most of the insulating liquids used in practice are small. If, however, high frequencies are used, high local heating may take place from the above reason, lowering the B.D.V. (see Peek[2]). On the other hand, the origins of dielectric loss in liquids are obscure and may depend upon the same factors which produce breakdown.

### (iv) *Effect of Continued Stress*

It is a matter of some importance to know whether an insulating liquid deteriorates in strength when subjected to continuous high stress. A few experiments have been carried out on this subject, but no definite results have been obtained. The E.R.A. investigated effects both on purified commercial oils and on pure liquids. Liquid was drawn by means of a syphon both from between spheres across which a high voltage had been applied for one and a half hours or so, and also from near the sides of the containing vessel. The samples were subsequently tested, and although there were wide variations between the results for the two sets of samples, there was not a sufficiently regular divergence to show a definite deterioration, but on the whole the results, particularly on pure liquids, make such a deterioration probable.

[1] Spath, *Archiv für Elektrotechnik* (30th June 1923).

[2] Peek, *Dielectric Phenomena*, ch. vi.

Crago and Hodnette[1] applied 100 kV between a needle and a plate, and measured the strength of the oil in the gap at intervals extending to an hour. They found that there was a fall in strength of about 10 per cent. in the first few minutes and little change subsequently. Short of actual breakdown, it is not to be expected that there would be much effect from continued stress upon a liquid, apart from the attraction of impurities to the gap. Cumulative heating, as in solid dielectrics, cannot easily occur, owing to the circulation and to the low power factor of good oil. Any deterioration observed would probably be due to the concentration of impurities and of weaknesses generally in the neighbourhood of the field.

### (*c*) Impulse Ratio

Under this heading the effect of frequency upon the B.D.V. of insulating liquids is considered. Instantaneous breakdowns are largely dealt with. Both Draeger,[2] who used 20-mm. spheres at 2·5 mm. in oil, and Sorge,[3] who used the German mushroom-shaped (V.D.E.) electrodes at 3 mm. in pure hexane, found that the breakdown voltage increases with higher frequencies (see fig. 53, A, B, C). According to Draeger[2] the strength does not vary much for frequencies above 400 cycles, but from Sorge's work it seems to be still increasing for hexane at 500 cycles. The latter, however, only obtained three points on the curve.

Hayden and Eddy[4] investigated the value of the ratio of the B.D.V. max. with direct current to the B.D.V. max. at 60 cycles for commercial Transil oil (No. 6) at different temperatures and with different rates of application of voltage. They found that the ratio increased with temperature and seemed to decrease when a longer gap was used. At 25° C. the direct current B.D.V. was less than the B.D.V. at 60 cycles, as in the case of gases when spark lag occurs, but at higher temperatures the direct current B.D.V. was often larger than the B.D.V. at 60

[1] Crago and Hodnette, Midwinter Convention, *A.I.E.E.* (February 1925).

[2] Draeger, *Archiv für Elektrotechnik*, **12** (August 1924).

[3] Sorge, *Archiv für Elektrotechnik* (1924).

[4] Hayden and Eddy, *J.A.I.E.E.* (July 1923).

cycles. A table of results is given in illustration. Petrolatum showed similar effects but a higher value of the ratio, which, in the case of most solids, is greater than unity.

| Electrodes. | Gap Length. (mm.) | Rate of application of Voltage. | Ratio $\frac{\text{B.D.V. with D.C.}}{\text{B.D.V. at 60} \sim}$. | | | |
|---|---|---|---|---|---|---|
| | | | 25° C. | 50° C. | 75° C. | 100° C. |
| 1 inch diameter spheres | 2 | 5% per sec. | 0·93 | 1·06 | 1·02 | 0·79 |
| | 4 | 5% per sec. | 0·86 | 0·83 | 0·9 | 0·9 |
| | 2 | 2% per sec. | 0·82 | — | 1·05 | — |
| | 4 | 2% per sec. | 0·76 | — | 0·86 | — |

Draeger[1] also investigated the effect of wave form upon the electric strength for oils of different purities (see fig. 53). The curves of breakdown strength/peak factor for oil in different stages of purification appear to be nearly parallel. The maximum values increase with peak factor while the effective values decrease. Peek[2] observed a reduction of B.D.V. at radio frequencies compared with 60 cycles.

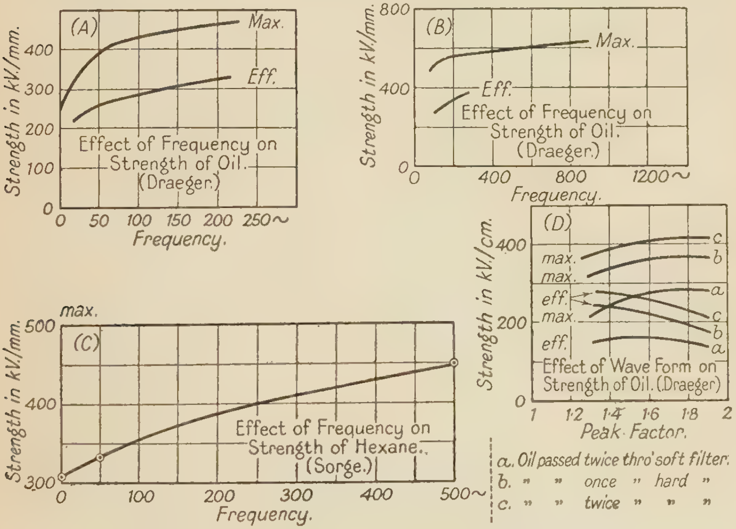

FIG. 53.—Effect of Wave Form on Electric Strength of Oil.

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[1] Draeger, *Archiv für Elektrotechnik*, **12** (August 1924).

[2] Peek, *Dielectric Phenomena*, ch. vi.

The distinction between the present section and the next, on transients, cannot be precisely drawn. In most of the experiments considered the applied voltage, which came from a source of unlimited energy, was rapidly raised until breakdown took place. Sorge[1] has found that rate of increase of voltage between 100 to 1300 volts maximum per second does not have any appreciable effect upon the breakdown strength (see fig. 54).

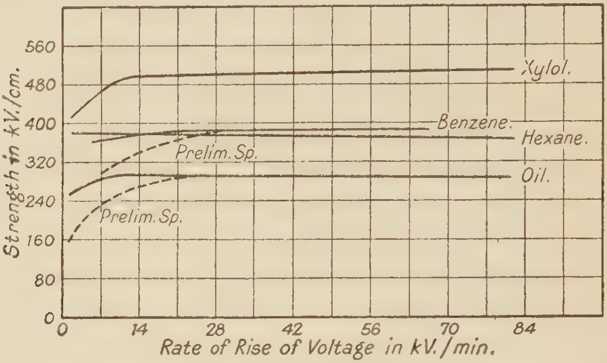

FIG. 54.—Effect of Rate of Rise of Voltage on Strength of Pure Liquids (Sorge).

Accordingly it is presumed that in these circumstances a type of breakdown occurs distinct from the case where a transient of limited energy is applied. Actually, of course, there is only a limited amount of energy involved, since the circuit opens before much energy is liberated. It is more convenient, owing to the differences in experimental procedure, to treat the phenomena separately. Since, in Sorge's[1] experiments, several seconds must have elapsed between the first application of the lowest voltage and the attainment of the final voltage, the observed increase of strength with frequency is difficult to interpret. The conclusion seems to be that either the higher frequency lessens the stability of chains and bridges, or that there is a time interval in the actual discharge which must be completed within the half-cycle.

On the other hand, Draeger's observation that the B.D.V. tends to constancy as the frequency increases is difficult to explain on such hypotheses. Some correlation is suggested with the anomalous conduction current which has less and less effect upon the permittivity as the frequency rises, but the connection is not clear. The observations of Hayden and Eddy that the 60-cycle B.D.V. decreases more rapidly with temperature than the direct current B.D.V. is also difficult to explain. It may be noted that, in this case, the B.D.V. decreased steadily with increase of temperature without showing a maximum. This would indicate that impurities had not any great effect, or that the decrease of viscosity did not affect their action. The variation of strength with wave form observed by Draeger[1] is interesting, as showing the importance of the effective voltage as well as of the maximum voltage. Further, it is to be noticed that the purification employed does not characteristically modify this aspect of the phenomena of breakdown. It should be remembered that, as in the case of air gaps, a higher impulse ratio does not necessarily mean a longer lag, for the lag may be shorter and yet the voltage may rise to a higher value owing to the steeper wave, so giving a higher impulse ratio or ratio

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[1] Sorge, *Archiv für Elektrotechnik* (1924).

$$\frac{\text{B.D.V. at given frequency}}{\text{B.D.V. at standard}}.$$

This only applies to instantaneous breakdowns.

The lowering of the B.D.V. at radio frequencies observed by Peek seems difficult to explain except on the hypothesis of losses as previously referred to. At low frequencies the losses in oil are very small.

### (*d*) Breakdown under Transients

When insulation of any kind is broken down a certain amount of energy is required. Accordingly, if an impulse of limited energy is applied to a gap, breakdown will not take place unless there is sufficient energy available. Thus the voltage in such an impulse will, in general, attain much higher values than in the case of a steady alternating or direct voltage. The effect of the steepness of the voltage rise has already been mentioned. Fig. 55 shows results obtained by Peek[2] comparing impulse sparkover voltages for fairly good commercial oil with 60-cycle values for needles and spheres. With needles the impulse ratio increases rapidly with the spacing. With spheres the curves for impulse and 60-cycle sparkover seem to be of the same form, except that the large spheres give rather anomalous impulse results at the longer spacings.

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[1] Draeger, *Archiv für Elektrotechnik*, **12** (August 1924).

[2] Peek, *G.E.R.* (August 1915).

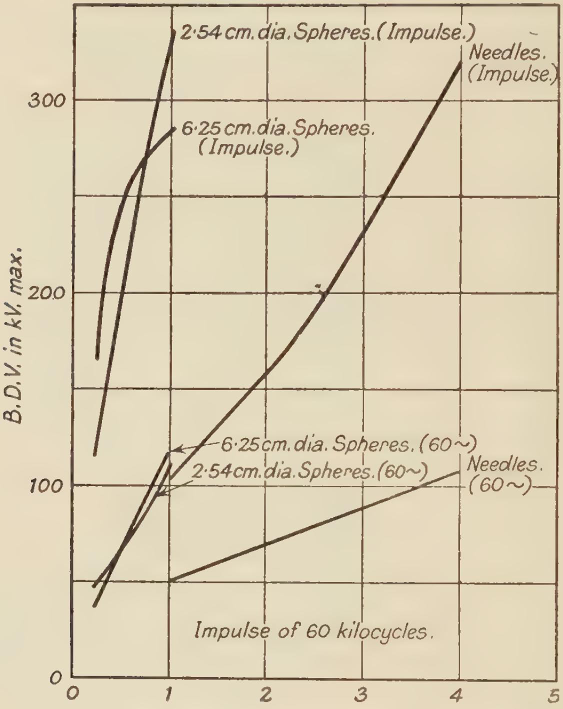

FIG. 55.—60~and Impulse Sparkover in Oil (Peek).

Hayden and Steinmetz[1] have applied impulses of limited energy contents, which could be measured on a relative scale, to needle and sphere gaps in oil. As may be seen from fig. 56, the voltage/distance curves vary in shape according to the energy of the impulse—curves are given for constant energy values. In the case of the needle gap the impulse voltage is greater than continuous applied voltage sparkover down to even the lowest spacings. In the case of the sphere gap the curves superpose at the lower spacings. For constant energy the spark-

[1] Hayden and Steinmetz, *A.I.E.E.*, **25** (1910).

over length increases with rise in maximum voltage, approaching a constant value hyperbolically—

$$V(d_0-d)=C^2 \quad . \quad . \quad . \qquad d4.1$$

V=maximum voltage, $d$=gap length, $d_0$ and $C^2$ are constants (see fig. 56). Thus, when the voltage is sufficiently high relative to the energy, the striking distance depends only upon the energy and not upon the maximum voltage. For needles the relation between the striking distance under these conditions and the energy is

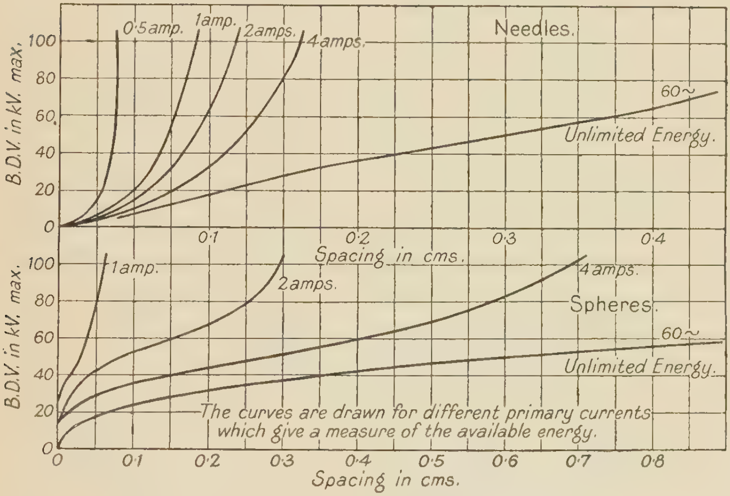

FIG. 56.—Breakdown under Transients for Paraffin Oil (Hayden and Steinmetz).

$$W=0{\cdot}235+0{\cdot}72d \quad . \quad . \quad . \qquad d4.2$$

For spheres the following equation was obtained,

$$W=10d^{1{\cdot}5} \quad . \quad . \quad . \qquad d4.3$$

It is generally found that the percentage variation between individual readings is much lower with impact voltages than with continuously applied voltages. This appears to be true both for pure and impure oils, and further readings may often be repeated on the same oil after several days and good agreement be obtained.

If several impulses are rapidly applied one after the other *e.g.* at the rate of several per second, the B.D.V., as might be expected, is considerably reduced. It has also been found that the irregularity of individual readings is considerably reduced when such impulsive stresses are used.[1]

Results, such as those obtained by Hayden and Steinmetz,[2] are interesting, not only on account of their application to switching surges, lightning shocks, etc., but also because the results should be more characteristic of the liquid itself than results obtained with sustained voltage. The time lag in these experiments must be of very short duration and insufficient for heterogeneous impurities to exert a preponderating effect. The experiments strongly support the view that a disruptive discharge through liquids requires not only a sufficient voltage but also a definite minimum energy. Further, the voltage/distance curves for different energies show that there must also be a time lag associated with the discharge.

In the case of the needle gap the energy/distance relation suggests that there is a definite minimum energy independent of spark length, and that further energy proportional to the spark length is required to spark across a given gap.

### (*e*) EFFECT OF WAVE FORM UPON BREAKDOWN UNDER CONTINUOUSLY APPLIED VOLTAGE

It is convenient to summarise briefly the effect of wave form upon the sparkover in the case of voltages applied in the usual manner, although some of the work has been mentioned in previous paragraphs. The general conclusion is that breakdown in liquids depends upon the effective voltage as well as the maximum voltage. In considering the effect of impurities this seems inevitable, since the mean square voltage is a measure of the average stress on a dielectric particle and the probable extent of the weakening of the gap by the collection of impurities in it. A high peak value for the voltage may compensate to some extent for a lower R.M.S. value, and, conversely, a high R.M.S. value often means that a lower peak value may produce

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[1] D. Burawoy, *Archiv für Elektrotechnik*, **16**, 186 (1926).

[2] Hayden and Steinmetz, *A.I.E.E.*, **25** (1910).

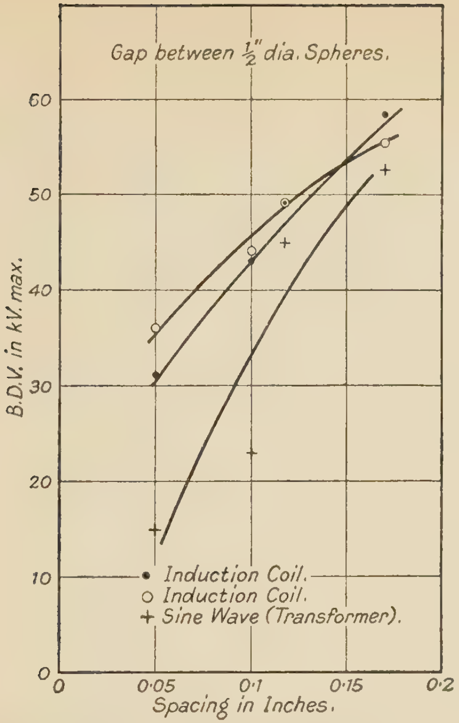

FIG. 57.—Effect of Wave Form on B.D.V./Spacing Curves for Good Oil.

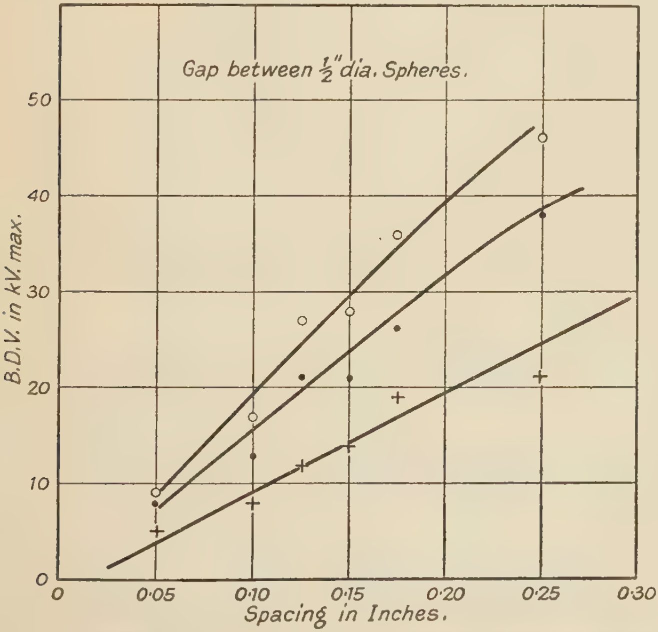

FIG. 58.—Effect of Wave Form on B.D.V./Spacing Curves for Bad Oil.

breakdown ; in this connection Draeger may be referred to (*loc. cit.*). The shape of voltage/spacing curves varies with the wave form, the B.D.V. (maximum) increasing with the peak factor (see fig. 57 and fig. 58). With good oil the curves for different wave forms sometimes seem to merge at the higher spacings. With a bad oil the divergence may become greater with a larger spacing.

# CHAPTER V

## EFFECT OF MATERIAL OF THE ELECTRODES

According to Sorge [1] the nature of the metal of the electrode exerts a considerable influence on the breakdown strength of pure liquids, as shown in the following table :—

| | Ag. | Zn. | Au. | Al. | Cu. | Pb. | Fe. | Brass. |
|---|---|---|---|---|---|---|---|---|
| Xylol . | 530 | 510 | 490 | 475 | 470 | 465 | 430 | 410 kV/cm. |
| Benzene . . | .. | 490 | .. | 450 | 455 | 430 | 390 | 420 kV/cm. |
| Hexane . . | .. | 470 | 430 | 440 | 435 | 386 | 350 | 365 kV/cm. |

This effect may arise either from the presence of surface layers, which, as in Zeleny's theory for air gaps, must be broken down before the discharge passes, or from some deteriorating effect of the metal upon the oil. It is known that copper and other metals may act as catalysts in producing sludging.

With reference to the effect of the preparation of the surface itself, Sorge [1] gives the following figures :—

| Surface. | Polished and cleaned with Benzene. | Unpolished. | With Layer of Grease. | Sand Blasted. |
|---|---|---|---|---|
| Strength in kV/cm. (on V.D.E. gap) . . | 400 | 375 | 385 | 370 |

The percentage deviation increases rapidly as the strength falls, being 15 per cent. for sand-blasted electrodes. A rise in breakdown when the surface is very highly polished has been observed with spheres in air.[2] Hayden and Eddy [3] in their tests on oil used molybdenum spheres, as these were least pitted by the discharge. Schroter [4] finds a considerable reduction in percentage deviation when the electrodes are properly cleaned instead of being polished merely with an oily rag.

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[1] Sorge, *Archiv für Elektrotechnik* (1924).

[2] Investigations at the B.T.H. Co. [See Report 2 (Great Britain), 63, presented at I.E.C., New York, 1926, and also *Electrical Discharges in Gases*, p. 57.]

[3] Hayden and Eddy, *A.I.E.E.* (July and February 1922).

[4] Schroter, *Archiv für Elektrotechnik* (March 1923).

# CHAPTER VI

## COMPARISON OF B.D.V. OF DIFFERENT LIQUIDS

It is difficult to compare the electric strengths of different insulating liquids owing to the relatively enormous variations, due to impurities, which may take place. Even if we only consider well-purified liquids, the difficulty arises as to how their electric strength should be expressed. The test on the standard gap can only give a relatively rough prediction of the behaviour of the liquid under other conditions. In considering the voltage/distance curves for insulating liquids in uniform fields we found that a linear law was obeyed. The coefficient of $l$ (gap length) in the formula

$$V=A+Bl \qquad . \quad . \quad . \quad . \quad e1$$

may be taken as a measure of the electric strength. Where these figures are not available, the sparkover voltage on the standard gap is given in the following table :—

| Liquid. | Chemical Constitution. | Standard Gap kV eff. | Strength kV/cm. eff. |
|---|---|---|---|
| Hexane . . | $CH_3(CH_2)_4CH_3$ | 42 (E.R.A.) | 234 (Sorge )[2] |
| Heptane . | $CH_3(CH_2)_5CH_3$ | 40 (E.R.A.) | 101 (E.R.A. from sphere gap at small spacings) |
| Octane . . | $CH_3(CH_2)_6CH_3$ | 51 (E.R.A.) | |
| Olive Oil . | .. | .. | 170[1] (at 0·2 mm.) |
| Turpentine . | $C_{10}H_{16}$ | .. | 160[1] (at 0·2 mm.) |
| Glycerine . | $CH_2OH.CHOH.CH_2OH$ | Very low | |
| Amyl Alcohol | $CH_3(CH_2)_4OH$ | Very low | |
| Xylol . . | $CH_3.C_6H_4.CH_3$ | .. | 433 (Sorge) [2] |
| Oil . . | Commercial insulating. An analysis of Switch Oil (Wakefield's Super Forma) for the E.R.A. gave a composition $C_{14}H_{30}$ | 50–60 would be a very good oil (over 90 kV has been obtained under special circumstances) | 180–190 (Highest readings from Sorge [2] and Spath [3]) |
| Benzene . | $C_6H_6$ | Highest readings would be 80–90 | 269 (Sorge) [2] |

[1] *Smithsonian Physical Tables.*

[2] Sorge, *Archiv für Elektrotechnik* (1924).

[3] Spath, *Archiv für Elektrotechnik* (30th June 1923).

Other liquids are given in the Smithsonian Tables, but the results are not considered very reliable, as they are based on early work, when the effect of different factors was not well known. It may be observed that the presence of a hydroxyl group reduces the strength of the liquid to a very low value. This we should expect, since the chemical activity of such a radicle indicates a strong polarity. The highest values are given by benzene and xylene, both ring compounds, which, from their structure, might be considered difficult to break up. Substitution of one of the hydrogen atoms of benzene is easy, but the break up of the ring itself would be difficult, and it is to be expected that in breakdown such a complete disintegration would take place, carbon and hydrogen being formed. Commercial oil and those of the paraffin series examined have fairly comparable strengths. Little variation is observed when passing from one paraffin to another. This also might have been predicted. On the other hand, the great difference between xylol and benzene is not easy to explain.

Flight[1] says that vegetable oils such as resin oil, linseed oil, and cotton seed oil, have much the same strength as mineral transformer oils. They are not used extensively in commerce owing to their high cost and tendency to sludge. Flight[1] also remarks that among commercial mineral oils those with the lower viscosity have the higher electric strength. We have already noticed that the positive temperature coefficient of electric strength has been explained as due partly to the reduction in viscosity. Such an effect would appear to be due to impurities, and the correlation of strength and viscosity is not generally agreed. Flight[1] gives the following table in support of his contention:—

| | | | |
|---|---|---|---|
| Viscosity of oil (° Redwood) . . | 26 | 12 | 10 |
| kV breakdown on standard gap used vertically . . . . . | 30 | 35 | 45 |

Tests also have been made on rare oils of high specific inductive capacity in connection with E.R.A. investigations. Some curves for almond, cedar, and sandal wood oils are shown on fig. 65 for small spacings. The breakdown strength appeared to follow a logarithmic law

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[1] Flight, *B.E.A.M.A. Journal* (February–March 1921).

$$g = \mathrm{A}d^{n} \quad . \quad . \quad . \quad . \qquad e2.1$$

*i.e.*

$$\mathrm{V} = \mathrm{A}d^{n+1} \quad . \quad . \quad . \qquad e2.2$$

(V=B.D.V., $g$=B.D. strength, $d$=spacing, $n$=constant less than unity.)

for small spacings. There seems, however, a tendency at higher spacings towards limiting strengths of the order of 60 to 90 kV/cm. [almond oil, 59 kV/cm. approx.; sandalwood oil, 83 kV/cm. approx.; cedar wood oil, 87 kV/cm. approx.].

# CHAPTER VII

## PRELIMINARY SPARKING AND CORONA

### (*a*) Preliminary Sparking

### (i) *Introductory*

As the voltage applied to a spark gap in oil is increased it often happens that a few isolated sparks may occur at a voltage much below that at which complete breakdown with arcover occurs. These initial sparks which do not completely bridge the gap are known as preliminary or pilot sparks. As the voltage is increased to the breakdown value they may, particularly in the case of impure liquids, become more frequent until, just before breakdown, there is a profuse and almost continuous discharge. Preliminary sparking is, however, neglected in standard commercial testing of insulating oils.

### (ii) *Relation with Impurities*

It is generally considered that preliminary sparking is due to the presence of stray impurities, and certainly it does not often occur if a liquid is very carefully purified. On the whole it is found that when the breakdown readings on a good oil are steady, pilot sparks are less liable to occur than when wide variations are met with during shots.

It has been found by the E.R.A. that, in general, less variation occurs in the values between the voltages at which pilot sparks pass in dirty liquids than between the corresponding breakdown voltages. This is also referred to by Garrard.[1] Sometimes, however, the pilot spark figures for a good oil approach the breakdown voltages as the oil becomes purer ; this might be due to the fact that in these cases the impurity causing the pilot spark was being removed by the purification. It is difficult to say whether any particular type or types of impurity give rise to a pilot spark. According to E.R.A. results, fibres in dry oil do not give pilot sparks, whereas fibres in moist oil do. Pilot sparks occur at various times after a purified oil has been exposed to a moist atmosphere, and it is suggested that pilot sparks appear when the oil becomes moist. The hypothesis of pilot sparks being due to small moist fibres has a certain amount of evidence in its favour. We can understand a partial discharge taking place owing to such impurities, and fibres are probably always present in impure oils.

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[1] Garrard, *Electrician* (21st August 1914).

On the other hand Schroter,[1] considers that a dry fibre bridge will give a pilot spark, the spark avoiding the bridge ; complete breakdown would occur if moisture were present. This theory seems at variance with a good deal of evidence on the effect of moisture. Sorge [2] has also observed pilot sparks with benzene and insulating oil, although apparently not with hexane or xylene. He used very pure liquids.

### (iii) *Influence of Gap and Electrodes*

Fig. 59 shows some curves for breakdown and preliminary sparking for different gaps in a low purity oil. The curves for pilot sparks and breakdown resemble each other in form, as is to be expected if the mechanism of discharge is similar, both being due to impurities. It may be mentioned that the voltage/spacing curves for pilot sparking and complete breakdown with rare oils (referred to in Chapter VI) also show this resemblance, following similar laws. Greater differences are observed for spheres and discs than for needles or point and plate—the former gaps are more sensitive to impurities. Sorge [2] also says that pilot sparks occurred with spheres and discs more often than with points. With pointed electrodes the preliminary discharge may become very profuse as the voltage is increased, and pilot sparks may turn into complete breakdown more easily with pointed electrodes than with other forms. Sorge [2] found that with pure liquids pilot sparks occurred with brass electrodes but not with other metals, and more frequently also when the electrode was sand-blasted than when carefully polished. It may be observed that under these conditions the percentage variation of the complete breakdown voltages was much greater. Pilot sparks are less frequent when the oil is hot than when it is cold.

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[1] Schroter, *Archiv für Elektrotechnik* (March 1923).

[2] Sorge, *Archiv für Elektrotechnik* (1924).

The effects just mentioned thus support to some extent the view put forward in the preceding paragraph, that pilot sparks are due to occasional moist fibres. We might also expect that in the case of very pure liquids pilot sparks would show greater

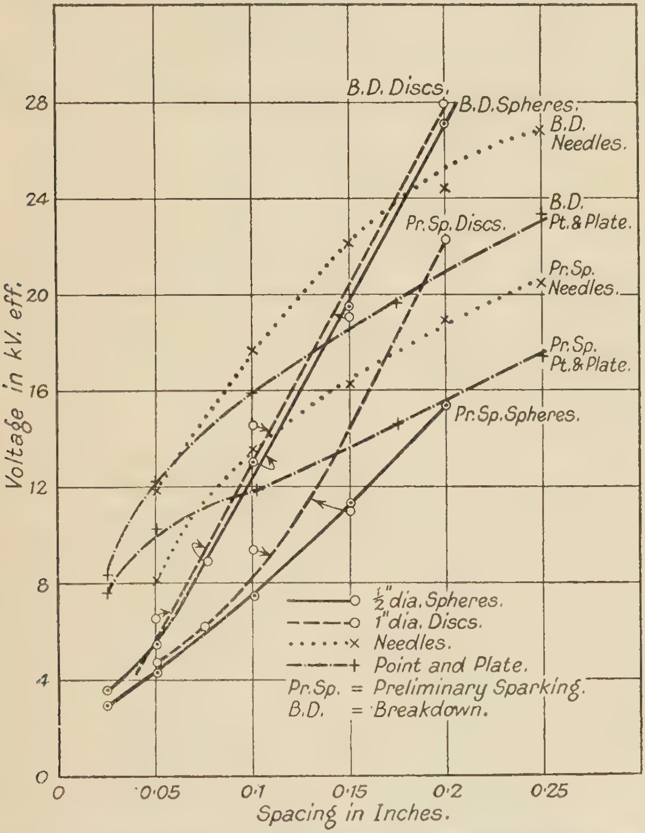

Fig. 59.—Comparison of B.D.V. and Voltage at which Preliminary Sparking begins for Electrodes of different Shapes Low Quality Oil.

differences the longer the field was applied, owing to the greater chance of a suitable fibre entering the gap. According to Sorge's work, as the rate of application of voltage increases, the pilot spark voltage increases much more rapidly than the complete breakdown voltage; the phenomena of preliminary sparking finally disappears when the rate of application of voltage is sufficiently great.

## (*b*) Corona in Liquids

### (i) *Introductory*

The phenomena of partial breakdown or corona in air are well known, and are of considerable importance in high-voltage engineering. A few investigators have found analogous phenomena to occur in liquids. They are, however, much rarer than with air, and so far little attention has been paid to the matter.

### (ii) *Experimental Work*

According to Moody and Faccioli[1] corona can be observed between needle points and point and plate in oil at relatively large spacings. It was also observed between a wire and a plate. When the discharge took place at the lower voltages there was an indication of an even but unstable glow of considerable thickness; at the higher voltages unsteady brushes appeared, a continuous glow being absent. Peek[2] also finds that corona in oil is unsteady, and that the luminous effects extend far out from the wire, which, in his experiments, was the corona-forming electrode. In experiments carried out for the E.R.A. the discharge appears to consist of a series of flashes, with sometimes an indication of a glow.

There is still doubt as to whether a true corona effect can occur in a liquid. No measurements have yet been completed on the effect of impurities, and the discharge does, indeed, resemble preliminary sparking in some ways. The general impression appears to be that corona, when it occurs in liquids, is not very greatly affected by impurities. Work carried out for the E.R.A. indicates that impurities in small quantities have little effect upon the critical voltage at which corona forms, although the sparkover voltage on the standard gap may have decreased considerably. When impurities are present in considerable quantity a large decrease is noticed and the nature of the discharge appears to change, being dependent upon the time of immersion of the electrodes and time of application of the electric stress. If the effect generally observed is a " glow " or a development of one, it would probably be characteristic of a homogeneous liquid, but some of the features observed may be the superimposed effects of impurities. Crago and Hodnette[1] say they have investigated the deteriorating effect of stresses upon oil below and above the corona voltage, but do not give details as to how the latter was determined, or describe the appearance of the discharge, apart from calling it " visible corona." According to Peek[2] corona cannot be obtained in oil unless the radius of the corona-forming electrode is such that the ratio of spacing to radius exceeds 300. The E.R.A. has found that corona can be obtained for much smaller ratios ; in one case, with dirty oil, sparkover and corona did not appear to coincide until the ratio of the radii of the concentric cylinders used was 15 : 1. It was also found, as with air, that the radius of the corona electrode was the determining feature so far as the critical gradient was concerned (see figs. 60 and 61). Peek has suggested that the gradient should follow the same law as for gases, viz.,

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[1] Moody and Faccioli, *A.I.E.E.* (1909).

[2] Peek, *Dielectric Phenomena*, p. 155.

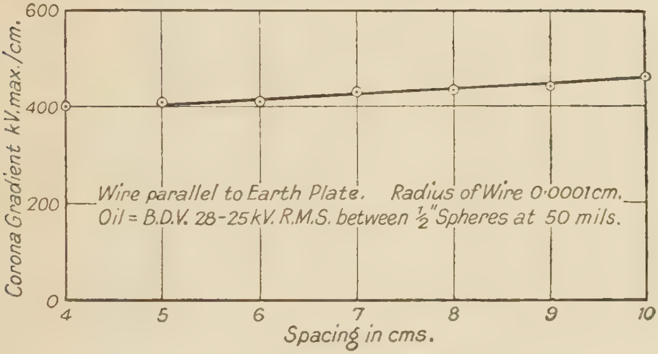

FIG. 60.—Effect of Spacing on Corona Gradient for Electrode of Constant Radius.

$$g_v=\mathrm{A}+\frac{\mathrm{B}}{\sqrt{a}} \qquad . \qquad . \qquad . \qquad . \qquad f1$$

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[1] Crago and Hodnette, Midwinter Convention, *A.I.E.E.* (February 1925).

[2] Peek, *Dielectric Phenomena*, p. 155.

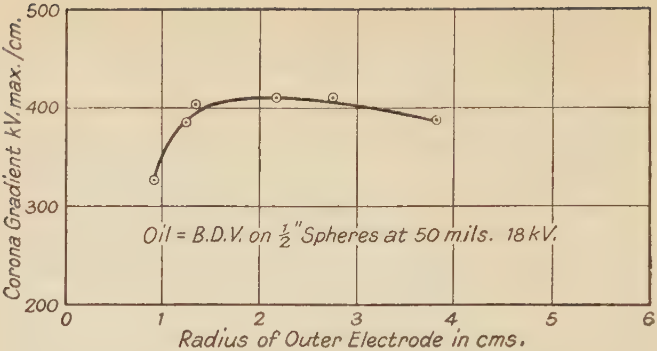

FIG. 61.—Effect of Radius of Outer Cylinder on Corona Gradient with Internal Cylinder of Constant Radius (0·0061 cm.).

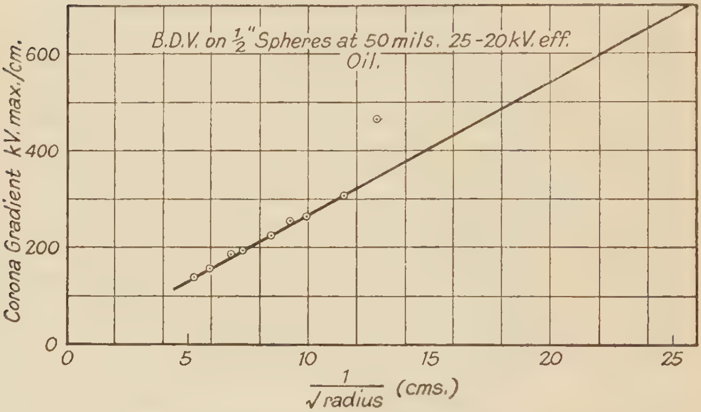

FIG. 62.—Effect of Radius of Cylinder (Cylinder and Plate Gap).

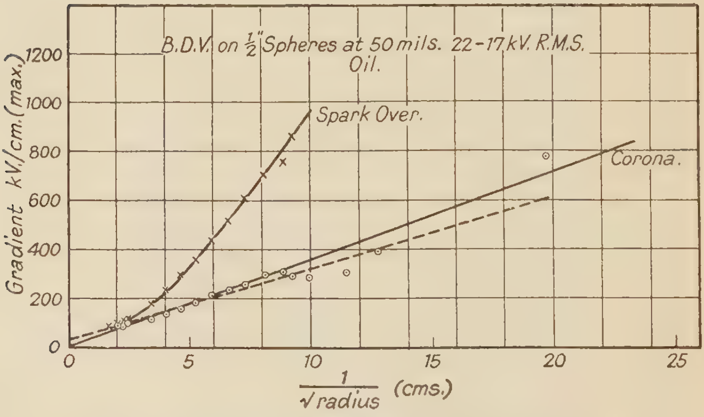

FIG. 63.—Effect of Radius of Outer Cylinder on Corona and Sparkover Gradients for Concentric Cylinders.

$g_v$=gradient at electrode, $a$=radius of electrode, A and B are constants. A certain amount of agreement with this was obtained by the E.R.A. in the case of concentric cylinders and wire and plate arrangement (see figs. 62, 63), but the evidence is not very conclusive. Fig. 64 shows the results obtained by Moody and Faccioli[1] for corona round points and round a wire opposite an earthed plate. At the present moment we cannot regard any laws as definitely established for corona in liquids. A more detailed account of the present situation with regard to the phenomenon is in course of preparation by the E.R.A.

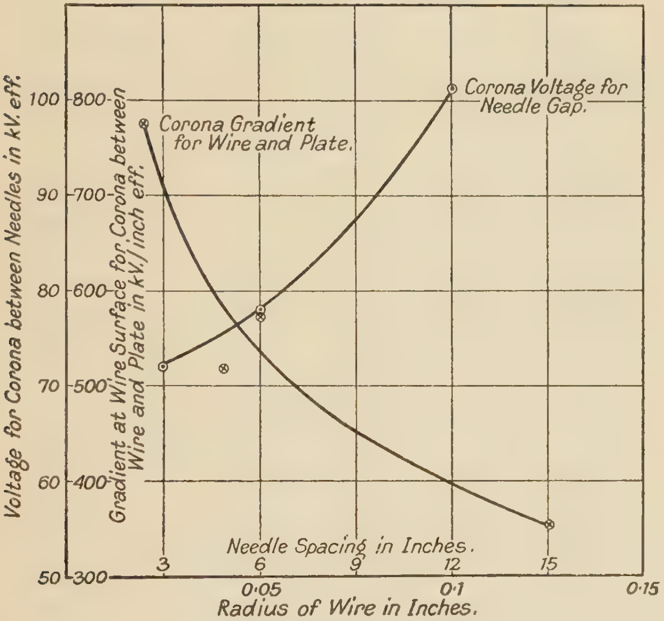

Fig. 64.—Corona Gradients and Voltages in Oil (Moody and Faccioli).

### (iii) *High Voltage Streamers in Oil*

It may be mentioned here that a phenomenon, which is probably allied to the corona considered above, is observed in oil tanks in which very high voltage testing is being carried out. Streamers appear, starting from sharp points and edges round nuts, bolts, and screw threads. They are somewhat similar to the brushes observed in air, but more unstable and of a lighter colour. These streamers occur at voltages considerably below breakdown, and probably bear the same relation to corona in oil which high-voltage brushes bear to corona glows in air.

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[1] Moody and Faccioli, *A.I.E.E.* (1909).

# CHAPTER VIII

## THEORIES OF BREAKDOWN IN LIQUIDS

### (*a*) Introductory

A theory can only be regarded as satisfactory when it is capable of explaining quantitative experimental laws. In the breakdown of liquids there are no quantitative experimental laws which are generally accepted. The theories put forward are, accordingly, qualitative; their range of application is difficult to determine, and in many cases their vagueness prevents exact criticism. Any theory which considers an insulating liquid as a homogeneous dielectric and neglects the effect of impurities can only have a very limited application, but, on the other hand, the theories concerning the effect of impurities are inclined to neglect the fact that, eventually, it is the liquid itself which breaks down.

### (*b*) Breakdown of a Pure Liquid

#### (i) *Phenomena of Breakdown*

In the first place, we must note the view that a perfectly pure liquid will not break down at all. This conception is analogous to the view that a gas completely free from ions has an indefinitely high breakdown strength. The consideration of whether a molecule or atom of a fluid can be ruptured solely under the influence of an electrical field is outside the scope of this résumé. Ions would probably be drawn out of the electrodes before such a disintegration took place. For present purposes we may consider a pure insulating liquid as a homogeneous isotropic fluid which possesses an extremely small but finite conductivity.

The passage of a spark through a liquid involves—

(1) The flow of a relatively large quantity of electricity determined by the characteristics of the circuit.

(2) A bright luminous path from electrode to electrode.

(3) The evolution generally of bubbles of gas and the formation of solid products of decomposition (if the liquid is of the requisite chemical nature).

(4) A pitting or burning of the electrodes.

(5) An impulsive pressure through the liquid with an accompanying explosive sound which may be more or less intense.

If the circuit remains closed, and if sufficient energy is available, a high-temperature arc will be formed. A certain amount of energy, determined by the conductivity developed, is spent in decomposing the liquid, in raising a part of it to a high temperature, and in producing carriers for the current. The state of affairs during the development of the discharge is unstable; the current rises rapidly and the discharge cannot persist, for either the energy of the circuit becomes exhausted or the discharge becomes an arc. At the beginning of the discharge the current must be

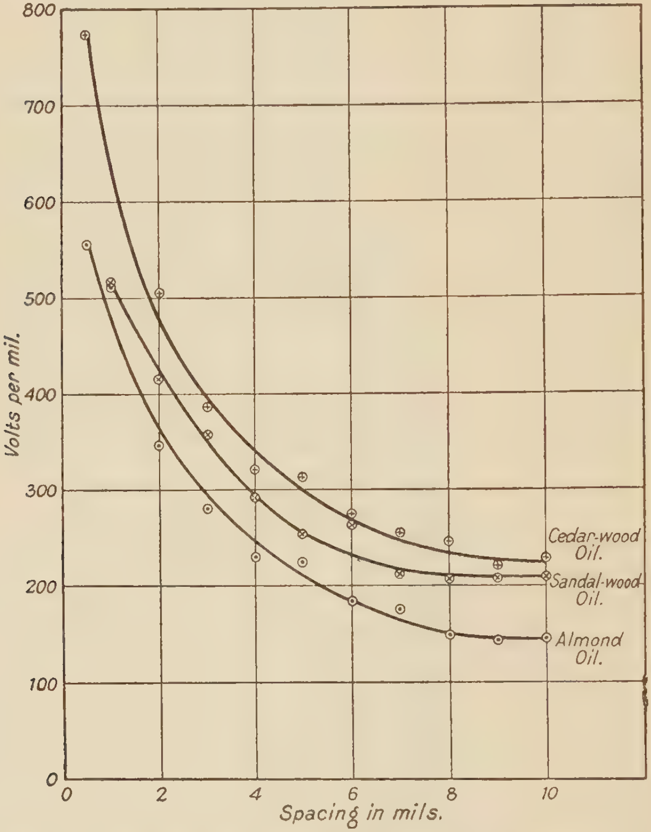

FIG. 65.—Strength of Oils between $\frac{1}{2}$-in. Spheres at small Spacings.

carried by the ions which give the liquid its normal conductivity. Finally, the current is generally carried by ionised vapour, an arc forming in a bubble of gas which extends round the gap. In the present instance the conditions which determine whether a discharge shall take place are the factors under consideration. Although the subsequent effects are the most characteristic they are not of importance here except in so far as they throw light upon the first causes and initial conditions.

The mechanism has been considered as developing in two ways :

(1) The ions originally present in the liquid acquire such energies in the electric field that they produce ionisation along their paths, the ions so formed produce further ions, and the discharge develops as in gases when ionisation by collision takes place. This mode of breakdown may be called ionisation by collision.

(2) The initial ions may produce so much heat along their paths that the oil is vaporised, and perhaps decomposed to some extent also, the vapour so formed breaks down, further oil is vaporised owing to the heat developed in the bubble of vapour, and the gap is bridged by a path of ionised vapour bubbles. This view may be called the vaporisation theory.

### (ii) *Ionisation by Collision*

The work of Gunther Schultze [1] and Poole [2] has shown that many conductivity effects in solid and liquid dielectrics can be explained on the supposition that the ions generate a certain number of further ions along their paths. In gases discharge phenomena can be largely explained (see *Dielectric Phenomena, Electrical Discharges in Gases*) on the hypothesis of ionisation by collision.

Peek [3] has adopted this theory in principle, for he considers breakdown in liquids to be analogous to breakdown in air. According to him, there exists a certain minimum breakdown strength for liquids as for gases, which may be linked up with the features of ionisation by collision, as in the résumé on gases above mentioned. The liquid does not actually break down whenever this minimum gradient or stress is reached ; the gradient, indeed, must be greater than the minimum breakdown strength over a certain distance, extending from the electrode and depending upon the curvature of the electrode, the magnitude of the distance being proportional to the square root of the radius. In liquids the constant of proportionality is large, so that the distance—known as the energy distance—is also large compared with gases. According to this theory the phenomena of breakdown in pure liquids should be analogous to those in air, except that the actual stress at the electrode on breakdown must be much larger in liquids, owing to their high minimum breakdown strength and to the fact that the extent of the field where the stress is higher than the minimum for breakdown is larger than for gases. Although other workers have not pressed the analogy with gases so far as Peek, yet there has been a marked tendency to consider that breakdown in particular cases is characteristic of the pure liquid when the laws obeyed resemble the laws applying to gases.

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[1] Gunther Schultze, *Zeitschrift für Instrumentenkunde* (March 1923).

[2] Poole, *Phil. Mag.*, **34** (September 1917) ; **42** (October 1921). Poole's results on the variation of conductivity at high stresses with the electric stress can be explained on the hypothesis that each ion generates a number of new ions proportional, on the average, to the path length described, and to the electric stress—or perhaps to the excess of the stress over a certain minimum stress characteristic of the liquid.

[3] Peek, *Dielectric Phenomena*, p. 155.

It is not necessary to assume that ionisation by collision takes place in liquids exactly as in gases in order to obtain laws similar to those arrived at on the above hypothesis. It is only necessary that an ion should produce a certain number of ions per centimetre of path, depending upon the field strength and the nature of the liquid. The mechanism by which this occurs does not affect the analogy and is not of immediate importance, since no satisfactory quantitative calculation has been made from first principles in the case of gases. The ionisation might occur indirectly through the liberation of heat by the moving ions. Assuming a constant mobility, the energy dissipated by an ion per second is proportional to $X^2$ where $X=$field strength. The rise of temperature in the neighbourhood of the ion can thus be expressed in terms of $X^2$. This rise of temperature might be considered as accelerating an ion-producing reaction in the liquid. The number of ions formed per second is thus a function of the temperature rise, and therefore of $X^2$. The number of ions formed per centimetre of path would thus be $\frac{1}{X}$ multiplied by a function of $X^2$. Thus, in effect, we might consider ionisation by collision to be taking place with a coefficient determined, as above, by the number of ions formed per centimetre of path.

The first difficulty with Peek's theory is that it is only partially satisfactory with respect to gases, and that the terms " minimum breakdown strength " and " energy distance " have no easily determined physical significance. Further, these terms refer, strictly speaking, to corona, and the application of them to sparkover involves at present empirical assumptions.[1] Although, as we have seen in considering the laws of breakdown of pure liquids in different gaps, there is some resemblance between the laws which pure liquids might be expected to obey and the laws relating to gases, yet the evidence is qualitative in character, and indicates that the divergences from Peek's laws which appear with air are exaggerated in the case of liquids.

It might be possible on the hypothesis of ionisation by collision to produce a discharge in a liquid without further decomposition apart from the formation of ions. Considering the close packing of molecules in a liquid and the intensity of the discharge fields involved, vaporisation and decomposition must occur very quickly, and it is difficult to imagine that the conditions for breakdown are independent of these effects. The external pressure influences breakdown of the type considered by the resultant compression of the liquid. The observed effect of the pressure on the breakdown strength is, however, too large when compared with the change in volume and molecular spacing involved.

It may be mentioned that if breakdown in liquids is presumed to be ionic in character, and if the equations of gaseous discharges, formally at least, be applied, a certain amount of agreement can be obtained with the observed effect of electrode shape; *e.g.* Peek's equation for the critical gradient for cylinders and spheres

$$R=A+\frac{B}{\sqrt{a}} \quad . \quad . \quad . \quad . \quad f1$$

---

[1] See *Electrical Discharges in Gases*—Corona, section v.

($R$=surface gradient, $a$=radius of electrode) might be obtained. Peek's equation, whilst being empirical so far as the numerical constants are concerned, has a form which can be derived from the "energy distance theory," although the latter itself contains an empirical assumption. Also, by assuming that the number of ions formed per unit length by a moving ion is proportional to the difference between the field strength and a minimum critical gradient,[1] a linear B.D.V./spacing relationship should be obtained for all forms of electrodes, provided the field were not very far removed from uniform, viz.,

$$V=a+X_0l \quad . \quad . \quad . \quad . \quad f2$$

$V$=B.D.V., $l$=spacing, $X_0$=minimum critical gradient, $a$=constant. The tendency for electrodes of different shapes to give rather similar voltage/spacing curves has been observed.

In the first volume of the present series Schumann's discharge condition for gaseous discharge is deduced,[2] viz.,

$$\int a dx=\text{constant} \quad . \quad . \quad . \quad f2.1$$

where $a$=number of ions formed per centimetre by a moving ion and the integration is taken over the spark path, the constant depending upon the gas and the sign of the ion considered. From this $f2$ may be deduced on the assumption considered above,

$$a=\lambda(X-X_0) \quad . \quad . \quad . \quad f2.2$$

where $\lambda$=constant, $X$=field strength. From the form of $f2.1$ the time for discharge should be approximately given by the time taken for an ion to pass from one electrode to the other, producing the number of ions required by $f2.1$. This time will decrease as the electric stress increases, and increase as the spacing increases. Both these features are observed (see Chapter IV), but as quantitative values are not available for mobilities of ions in insulating liquids at higher stresses, satisfactory calculations have not so far been made. The spark lag values of Iwatake suggest mobilities of the order of those of gases, thus favouring to some extent the vaporisation or gaseous path theory considered below. It seems, however, that the finite velocities of ions only account for a part of the spark lags occurring in practice, since the latter are frequently of too high an order for a simple ionic explanation. The lag considered above has a limiting maximum value depending upon the spacing and the minimum B.D.V. at this spacing. It is, however, difficult to conceive that the time lag should be finite even when the applied voltage approaches infinitely closely to the critical voltage unless the presence of quantum effects gives rise to some further discontinuity condition. If the treatment is based on ionisation coefficients as functions of the field strength, then an infinite time lag occurs at the critical voltage. Formulæ may be deduced for the rise of current during discharge, assuming Townsend's theory of ionisation by collision. The following, which is for a uniform field, is one of the most convenient :—[1]

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[1] *Vide supra*, Poole.

[2] *Electrical Discharges in Gases*, p. 30.

$$\text{logh}\,\frac{i_t}{i_0}=\text{E}(u+v)t\frac{\beta-\alpha e^{(\beta-\alpha)l}}{1-e^{(\beta-\alpha)l}} \quad . \quad . \qquad f\,2.3$$

where

$i_t$=current after time $t$.
$i_0$=initial conduction current.
E=electric force applied.
$\alpha$=ionisation coefficient for negative ions.
$\beta$=ionisation coefficient for positive ions.
$u$=mobility of negative ion.
$v$=mobility of positive ion.
$l$=gap length.

When $\beta=\alpha e^{(\beta-\alpha)l}$, *i.e.* at the critical voltage, $t=\infty$ if $i_t>i_0$.

It was mentioned above that if we might put

$$\frac{\beta}{\alpha}=\text{constant}=k \text{ and } \alpha=\lambda(\text{E}-\text{E}_0),$$

then a linear relation would be obtained between the B.D.V. and the gap length. If these substitutions are made in the present equation then the following approximation can be obtained :—

$$\text{logh}\,\frac{i_t}{i_0}=\text{E}(u+v)k\alpha\lambda(\text{V}-\text{V}_1)t \quad . \quad . \qquad f2.4$$

where $\text{V}_1$=minimum critical B.D.V. or sustained B.D.V.

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[1] Braunbek, *Zeitschrift für Physic*, **391**, 6–23 (1926).

$V_1$ will satisfy the linear relation

$$V_1 = E_0 l + C$$

where
$$C = \frac{\operatorname{logh} k}{\lambda(k-1)}.$$

Thus the following equation may be obtained :—

$$t\left[\frac{k^{\frac{1}{2}} \operatorname{logh} k}{k-1}\right]^2 = \frac{\operatorname{logh} \frac{i_t}{i_0} l^2 C^2}{V(V-V_1)(V-V_1+C)(u+v)}. \qquad f2.5$$

Consider now the highest readings of a pure oil such as that mentioned in Chapter II, section (*a*), giving a B.D.V./spacing relation

$$V_1 = 10 + 193l \text{ kV}$$

over a short range.

The mobilities of ions in an aqueous solution vary from 1 to 1·4 cm./second per *k*V/cm. Adopting the values $u=v=1$ and $l=0{\cdot}5$ cm., then for this oil,

$$t\left[\frac{k^{\frac{1}{2}} \operatorname{logh} k}{k-1}\right]^2 = \frac{\operatorname{logh} \frac{i_t}{i_0}}{0{\cdot}08V(V-106{\cdot}5)(V-96{\cdot}5)}. \qquad f2.6$$

If
$$\operatorname{logh} \frac{i_t}{i_0} = 20$$

the current can be considered to have risen from about $10^{-10}$ amp. to 0·1 amp., which is taken here as a criterion of breakdown. In this way a time-voltage curve has been calculated on fig. 66. The time scale cannot be determined until $k$ is known, but this is a ratio characteristic of the liquid.

The approximations introduced in deriving equation *f*2.4 are less valid for liquids than for gases, owing to the greater number of ions formed per centimetre. A more satisfactory form would be

$$\operatorname{logh} \frac{i_t}{i_0} = \frac{V(u+v)(\phi-1)k\lambda(V-V_1+C)}{(\phi-k)l^2}. \qquad f2.7$$

where
$$\phi = e^{\lambda(1-k)(V-V_1)} \quad \text{and} \quad C = \frac{\operatorname{logh} k}{\lambda(k-1)}$$

as before.

### (iii) *The Vaporisation Theory*

According to this theory, when the field is sufficiently strong the ions originally present begin to dissipate such large quantities of energy that the liquid is vaporised, and also, perhaps, broken down into solid products and gases. The gas bubbles so formed break down, giving local heating and formation of further gas until all the characteristics of the discharge appear. Hayden and Steinmetz[1] have advanced the theory that breakdown is due to the formation of gas bubbles, while Draeger[2] has stated that it is due to quickly moving ions with high friction producing vapour paths in the liquid, while slower moving ions with long mean free paths may also give ionisation by collision. Priority in this theory is probably due to Gunther Schulze (*vide supra*), who also applies it to solids.

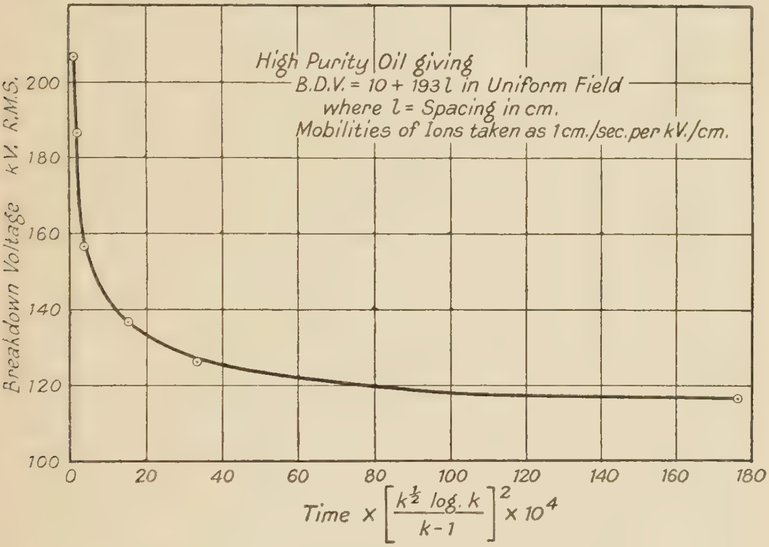

FIG. 66.—Theoretical Form of B.D.V./Time Curve from Ionic Discharges Theory.

The theory brings together the main phenomena of the actual discharge. The large current is due to the formation of a path of ionised vapour; the decomposition may be an intrinsic part of the mechanism, as also the evolution of gas. The high temperature accounts for the brightness of the spark, and the probability that the bubbles are formed under a considerable impulsive pressure may account for the fact that the luminosity in liquids approaches more nearly in appearance that of an incandescent body than in the case of gases. The stress necessary to produce these effects would depend upon the nature of the available ions, and also upon their number. Accordingly, variable results with apparently identical pure liquids may be expected, and the conductivity, preferably measured at a high field strength, should give an indication of the relative breakdown strength. The effect of pressure can be easily understood, since bubbles will form with much greater difficulty in a liquid under compression.

---

[1] Hayden and Steinmetz, *A.I.E.E.* (January 1924).

[2] Draeger, *Archiv für Elektrotechnik* (12th August 1924).

It appears that a pure liquid has a small negative temperature coefficient of electric strength. As the boiling-point is approached vaporisation takes place more readily the larger the specific heat and the greater the ratio of the specific heat to the latent heat. We do not, however, find corresponding variations in the temperature coefficients of different liquids, and in cases where the specific heat and boiling-point are high, the temperature coefficient is generally less than one would expect in comparison with liquids of lower specific heat. The energy required to vaporise the liquid from room temperature, *i.e.* the "total heat," should also have a determining influence. To this must be added the energy of dissociation and ionisation, but the energy expended in this way does not appear to vary very greatly among the hydrocarbons generally used as insulators, provided the energy is reckoned per ion produced. Otherwise the more complex molecules would require a greater energy per gramme molecule owing to the greater number of ions eventually produced. In the present theory we are mainly concerned with the formation of vapour paths which will depend in the first place upon the total heat. In the case of the hydrocarbon series (both aliphatic and aromatic) the boiling-points and the specific heats increase with the order of homologue. On the other hand, the latent heat tends to decrease, and since the latent heat may form two-thirds of the total heat, the net result is that the total heat does not vary to a very large extent. Extensive data are not available for the variation of specific heat with temperature in the case of insulating liquids, so that comparisons are only approximate, but it is possible that the relatively small variation in electric strength found in passing from one homologue to another among the hydrocarbons may be connected with the correspondingly small variation of total heat. But if an attempt is made to extend the correlation as between compounds of different structures, anomalous results are obtained. The following figures for one or two insulating liquids give an idea of the order of magnitude of the quantities mentioned :—

| Liquid. | Boiling-point, ° C. | Specific Heat (temperature), Small Calories.<br>° C. | Latent Heat, Small Calories. | Notes. |
|---|---|---|---|---|
| Benzene | 80·1 | 0·34 (10)<br>0·423 (40)<br>0·482 (65) | 92·9 [1] | [1] 127·9 (total heat from 0°C. measured). |
| Toluene | 111 | 0·364 (10)<br>0·490 (55)<br>0·534 (85) | 86 | |
| Aniline | 184 | 0·514 (15)<br>0·520 (30)<br>0·529 (50) | 110 | |
| Glycerine | 290 | 0·576 (15–50) | | |
| Petroleum | | 0·511 (20–60) | | |
| Heptane | 90 | .. | 77·8 | |
| Hexane | 70 | .. | 79·2 | |
| Switch Oil ($C_{14}H_{30}$) | 370 | 0·6 | 52 [2] | [2] Total heat from 0° C. =274 calories.<br>Gross heat of combustion = 19,800 calories per gramme. |

### (c) Breakdown of a Contaminated Liquid

Impurities can be conceived as acting in four ways :

(i) The short circuiting of the gap by means of a conducting bridge.

(ii) The effective shortening of a gap by a chain attached to one electrode.

(iii) A homogeneous deterioration of the liquid by the formation of an intimate mixture.

(iv) The effect of isolated nuclei in the gap.

### (i) *Bridges*

The evidence is very strong that the majority of low breakdowns in impure liquid are due to the presence of moist fibres, which probably form chains bridging the gap. In an impure liquid such chains are probably conducting, since, if they are not so *per se*, they will contain impurities either dispersed through their volume or adsorbed on their surface. Fibre bridges, even in a very pure oil, will often be conducting owing to their being loaded with air which breaks down under the electric stress. The only exceptions will be bridges formed of a dielectric stronger than the ambient medium, which itself, apart from the particles of the bridge, must be absolutely pure.

The mechanism of the breakdown following the establishment of a conducting bridge will be analogous to the blowing out of a fuse. A heavy current flows through the bridge, disintegrating it and giving an intense local heating. The liquid in the neighbourhood is decomposed and vaporised, the gaseous products themselves breaking down and giving the characteristic discharge phenomena. It is necessary that the energy given out during the destruction of the bridge should be sufficient to produce enough bubbles of gas or vapour in the liquid to ensure complete breakdown. Otherwise the bridge may be burnt away without complete sparkover—as is generally thought to happen in preliminary sparking. The voltage necessary to destroy the bridge will also depend not only upon the material of the bridge, but also upon the thermal conductivity of the oil. In general, however, the electrical overstress is of itself sufficient to destroy the bridge, since breakdown will usually take place too quickly for the thermal conductivity to have much effect. For a bridge of the same material in a given liquid it is to be expected that the current required for breakdown, and therefore the electric strength, would be independent of the gap length if the cross-section were also constant. As the cross-section of the bridge increases compared with the length, the strength would probably decrease, for the breakdown current required would not increase so rapidly as the resistance decreases. Thus the strength would be smaller at the shorter spacings. In the analysis of results in Chapter II these effects appear sometimes to be encountered.[1]

### (ii) *Effective Reduction of the Gap by Impurities*

If a chain of impurities or a fibre becomes attached to one of the electrodes it will eventually acquire the potential of the electrode, so that the latter can be considered as replaced by a needle point and the gap shortened. Breakdown may then ensue either as in the case of a pure liquid or as for a liquid modified by the effect of impurities other than those forming the chain or bridge.

With regard to the former type, we know that a gap with a pointed electrode or electrodes breaks down at a lower voltage in pure oil than with a more uniform field. It should be possible to correlate certain readings on a sphere gap in a fibrous oil with readings for the same oil when free from fibre on a needle gap or point and plate gap. We could not, however, be sure that the results on the latter gaps were not affected by some peculiar disturbing factor, and the forms of voltage/distance curves for different gaps (as so far determined) are not sufficiently characteristic for resemblances to be easily detected. If the breakdown from the end of the fibre depended itself upon other impurities present, then, in some circumstances, it should be possible for the presence of the fibre to raise the breakdown voltage, as with points in impure oil the B.D.V. is higher for the same length of gap than for more uniform fields. In the case of pointed electrodes their curvature is often reduced by the concentration of impurities round them, with the result that the B.D.V. is raised. Breakdowns of the type considered here should show a characteristic type of time lag due to the resistance of the chain in series with the gap. When the stresses are high, insulating oils are almost invariably used in service with solid barriers to prevent the alignment of impurities. By using a series of thin layers of oil a higher mean strength should be obtainable than with a single thick layer. The flux distribution is, however, a difficulty, and if metal intersheaths are introduced to grade the flux then their mechanical problems and the difficulty of oil-tight joints give rise to trouble. It is sometimes possible to save trouble by metallising one of the surfaces of each spacer, as by this means the protection against alignment is still retained. There is no definite evidence as to any differences between the breakdown of liquids contained between solid dielectrics and when in a similar field but contained between metallic electrodes.

---

[1] In the chapter referred to it was found that in the voltage/distance formula $V=A+Bl$, A might occasionally be zero or negative when a small range was considered. If $A=0$, strength$=\frac{V}{l}=B=$constant. If A is negative, the strength is zero at a given distance and increases as $l$ increases.

### (iii) *Homogeneous Deterioration of the Liquid*

If a foreign substance is mixed sufficiently intimately with the liquid then, from the point of view of breakdown, a new liquid may be produced. On the hypothesis of ionisation by collision, if these foreign molecules or aggregates require a comparatively small amount of energy for ionisation, then a discharge may be carried by them if sufficiently numerous. The breakdown will in this case be characteristic of the impurity. On the other hand, if the impurity is present only in small quantities, it will not have much effect in this manner, but it may modify the breakdown characteristics by condensing round the ions and reducing their mobilities. On the hypothesis of vaporisation, the impurity may more readily give bubbles of gas or vapour, and so lower the B.D.V. It may also affect the B.D.V. by providing initial ions or by altering the mobilities of ions already present. These last two effects should become apparent in a study of the conductivity previous to breakdown.

Again, if decomposition of the liquid is an essential factor in determining breakdown, then the impurity may act catalytically ; if any chemical process is a necessary part of the phenomenon, this effect may take place. These remarks have an especial significance for water, since it is believed that in the absence of moisture few or no chemical reactions will take place. In fact, in all the modes of breakdown considered under the heading of the vaporisation theory, water should have some intrinsic effect.

### (iv) *Isolated Particles in the Gap*

The effect will now be considered of isolated particles or aggregates of particles which neither bridge the gap nor, by becoming attached to an electrode, shorten it. In the first place, such bodies may cause concentration of flux in their neighbourhood and initiate local breakdown. On the hypothesis of ionisation by collision, this effect does not seem likely to be very important. Owing to the high retarding forces to the motion of an ion in a liquid, the intense part of the field must be of fairly considerable extent in order to give the ion space in which to gain speed. Using Peek's nomenclature, the " energy distance " in insulating liquids is large. If the views of the vaporisation theory are adopted, these bodies have a more important effect. Such bodies as gas bubbles, fibres loaded with gas, suspended semi-conducting liquids, etc. may themselves break down, giving bubbles of gas or vapour. Isolated particles may also serve as nuclei round which bubbles of gas and vapour, produced by moving ions, may form. In either case the result is the formation of bubbles of gas or vapour. If the bubbles are sufficiently large originally, and if the stress is sufficiently high, then so much energy will be generated within them that progressive vaporisation and decomposition of the liquid will take place in the neighbourhood, the bubbles at the same time elongating in the field of force until the electrodes are bridged. The critical length of such a bubble will possibly be a function of the rate of generation of energy within it (see Dubois [1]). If the bubble were small initially, or if the stress is too small, then the rate of generation of energy will not be large enough, and the bubble may be removed from the field before complete breakdown takes place. Preliminary sparking may sometimes occur in this manner.

### (v) *Variations Subject to the Laws of Probability*

Hayden and Eddy [2] have made large numbers of tests, using samples of the same oil and the same electrodes. They found large variations between different tests, and, further, that if the test voltage is plotted against the number of tests giving that voltage, then the points lie nearly, but not quite, on a normal probability curve around a most probable mean value. From this they deduced that oil shows in its essential nature a relatively large factor of variation. It is, however, difficult to believe that this is a characteristic of a pure liquid, and not of a liquid modified by foreign substances. There is no reason to believe from evidence on other properties of liquids that such lack of homogeneity occurs in the composition. On the vaporisation theory the impulsive pressures due to circulation currents might possibly give a probability variation. During the consideration of the effect of the area of the electrode upon the B.D.V. for discs, some curves by Farmer (see fig. 30) were given showing a regular decrease of B.D.V. (Farmer plots electric strength actually, but the gap length was constant) with increase of electrode area, the B.D.V. bending asymptotically to a minimum value.

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[1] Dubois, *A.I.E.E.* (1922).

[2] Hayden and Eddy, *A.I.E.E.* (July and February 1922); also Hayden and Steinmetz, *Trans. A.I.E.E.*, 42 (1923), 1032.

The general course of the curve can be explained by considering the chance that an impurity should enter the gap. The impurities may be divided up into classes having in conjunction with the oil a given breakdown voltage V for the given gap, and a density of distribution $n$. $n$ may be regarded as a function of V. Suppose $V_0$ is the lowest, such B.D.V. and V′ the B.D.V. of the pure oil. Let A=area of electrode. The proportion of readings giving $V_0$ the lowest breakdown

$$=1-\lim_{r=\infty}\left(1-\frac{n_0 A}{r}\right)^r=1-e^{-n_0 A} \quad . \quad . \quad . \quad f3$$

The proportion giving $V_1$ the next lowest breakdown=probability that $V_0$ is not given multiplied by probability that $V_1$ is given

$$=e^{-n_0 A}(1-e^{-n_1 A}) \quad . \quad . \quad . \quad . \quad f4$$

The proportion giving $V_2$ the next lowest breakdown

$$=e^{-(n_0+n_1)A}(1-e^{-n_2 A}).$$

The mean B.D.V.

$$=V_0(1-e^{-n_0 A})+V_1 e^{-n_0 A}(1-e^{-n_1 A})$$
$$+V_2 e^{-(n_0+n_1)A}(1-e^{-n_2 A})+\ldots$$
$$=V_0+(V_1-V_0)e^{-n_0 A}+(V_2-V_1)e^{-(n_0+n_1)A}+ \quad . \quad f5$$
$$=V_0+\int_{V_0}^{V'} e^{-mA}dV \text{ proceeding to the limit} \quad . \quad . \quad f6$$

where $m$ is given by $$n=\frac{\partial m}{\partial V}dV.$$

We can, by taking one or two classes of inhomogeneity, obtain a fair approximation to the experimental results. The breakdown values $V_0$, $V_1$, etc. should appear in the actual readings, but these are not given. If the hypothesis of Hayden and Eddy [1] is true we should be able to calculate V, $n$, and $m$ from the distribution curve for given electrodes, and then should be able to predict the distribution curves and mean B.D.V.'s for electrodes of larger area as above. The calculation is given on account of its academic interest only, for although it may be applied with some success to the hypothesis of "weak spots" in varnished cloth, papers, etc., the premises do not really apply in the case of oil, owing to circulation effects and the motion of impurities under the influence of the electric field.

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[1] Hayden and Eddy, *A.I.E.E.* (July and February 1922).

# APPENDIX

## STANDARD METHODS FOR TESTING THE ELECTRIC STRENGTH OF INSULATING LIQUIDS

### GREAT BRITAIN

### *Insulating Oils*

THE sample is first thoroughly shaken in order to distribute possible impurities, and the voltage applied before settlement takes place, but not before all visible air bubbles have disappeared. The container and electrodes are cleaned and dried, dust and fibres being removed as follows: The containing vessel is filled with the oil, half the test voltage is applied for thirty seconds, the electrodes are washed with fresh oil, and the oil in the vessel is poured away. The operation is repeated four times, after which the container may be used for twenty tests without recleaning.

The minimum internal dimensions of the test cell are 55 mm. × 90 mm. × 100 mm. (high).

*The electrodes are* 13 *mm. diameter brass spheres mounted horizontally at a spacing of* 4 *mm.* (0·157 *inches*), *immersed in the oil to a distance not less than* 50 *mm.* (*or* 2 *inches*) *from the surface* (see fig. 67 on opposite page).

The volume of the oil should not be less than 300 c.c. per test. The temperature of the oil should be 15·5°–20° C. (60°–68° F.).

The test voltage should have a frequency of between 25 and 100 periods per second and be of sine wave form (having a peak ratio not greater than 1·45), and is increased from 10 kV as rapidly as consistent with measurement up to either the full test voltage or until complete breakdown (the establishment of an arc) takes place. The voltage is expressed in R.M.S. values (either by direct measurement of the effective value or by dividing the observed peak value by $\sqrt{2}$).

(The above is abstracted from B.S.S. 148.)

### U.S.A.

### *Sampling*

The method of sampling is given in considerable detail, the main features being that the sample should be taken from the bottom of the drum and should be about a quart.

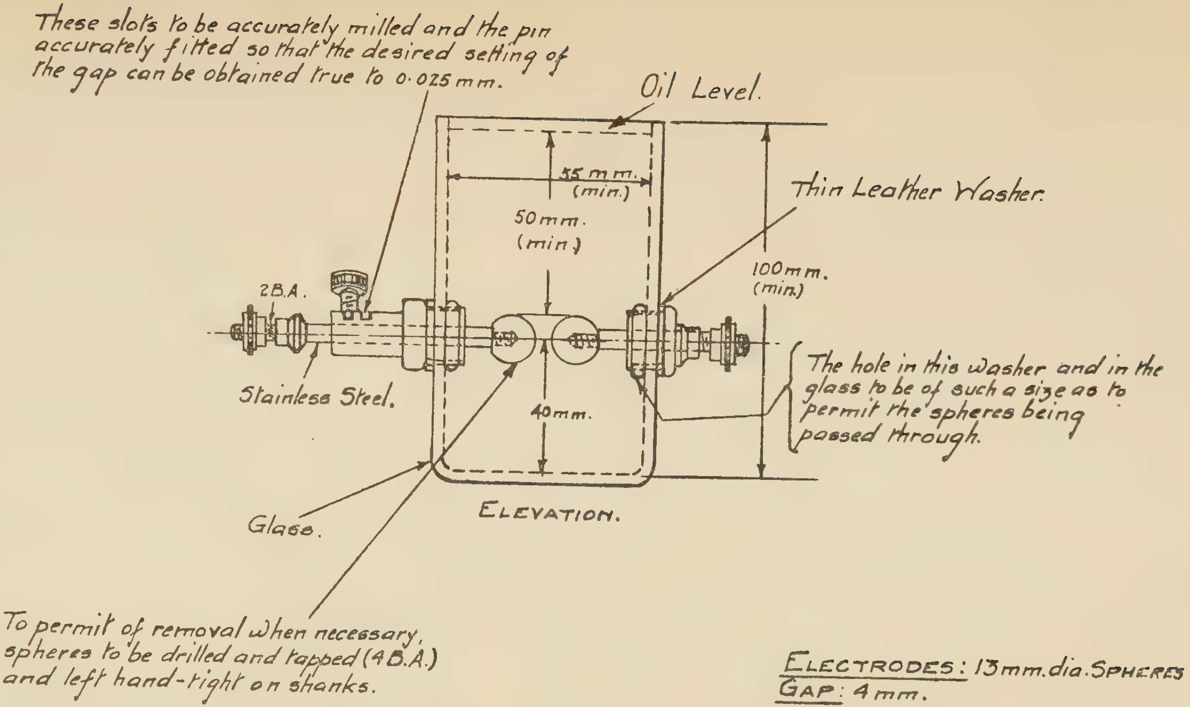
These slots to be accurately milled and the pin accurately fitted so that the desired setting of the gap can be obtained true to 0·025 mm.
Oil Level.
55 mm. (min.)
50 mm. (min.)
Thin Leather Washer.
100 mm. (min.)
2B.A.
Stainless Steel.
40 mm.
The hole in this washer and in the glass to be of such a size as to permit the spheres being passed through.
Glass.
ELEVATION.
To permit of removal when necessary, spheres to be drilled and tapped (4B.A.) and left hand-right on shanks.
ELECTRODES: 13 mm. dia. SPHERES
GAP: 4 mm.

FIG. 67.—Standard Method for testing the Electric Strength of Insulating Oils.

### *Testing Apparatus*

A high tension transformer is used giving at least 2 kVA for voltages up to 50 kV, or at least 5 kVA above 50 kV; the frequency must be not more than 100 periods per second and the wave form different from sinusoidal by not more than 10 per cent. The voltage is measured by some device giving R.M.S. values; a spark gap may be used as a check.

*The test gap is between* 1 *inch diameter polished brass or copper circular disc electrodes with a square edge and spaced* 0·1 *inch apart* (*between adjacent faces*), *immersed to a depth not less than* 20 *mm.*

### *Method of Test*

The electrodes and container are rinsed with oil-free gasoline until free from fibres and also with a sample of the oil.

The temperature of the gap and sample must be between 20° C. and 30° C.

The voltage is applied at 3 kV per second until a continuous discharge occurs.

Five breakdowns are made on each filling, the primary being broken as soon as possible after breakdown on each shot.

The value for each " shot " and the temperature is noted. (The above is abstracted from A.S.T.M., Serial No. 117/24.)

## GERMANY

### *Sampling*

The oil is taken from the lowest point of the apparatus at the deepest spot.

### *Test Apparatus*

*The gap is that between two* 25 *mm. radius copper spherical surfaces. The standard fixed spacing is* 3 *mm.*

The sphere surface must be at least 12 mm. from the walls of the glass or porcelain container. The leads must be at least 45 mm. apart and of diameter not less than 5 mm. The transformer must give at least 30 kV and 250 VA. The circuit must not allow more than 0·5 amp. to pass on discharge.

### *Method of Test*

At least 0·25 litre of oil must be used. The electrodes and container are polished with leather, washed with benzol, and rinsed with the oil. The oil is left still ten minutes before switching on.

If the spacing is fixed, the voltage is applied so that breakdown occurs in about twenty seconds. If the spacing is varied, breakdown should also occur in about twenty seconds. The voltage observed on the standard gap is expressed in terms of electric strength by multiplying by 3·5. If the gap is varied, the factor is obtained from a published curve. Six shots are made, but the average is computed from the last shot.

Air bubbles in the oil are to be avoided by pouring the oil slowly down the sides of the vessel.

### France

Precautions as to sampling, test apparatus, etc. are similar to the V.D.E. specifications.

The gap used is between 12·5 mm. diameter discs spaced 5 mm. apart.

### Belgium

The standard gap used is that between 10 mm. diameter spheres mounted vertically at a spacing of 2 mm.

### Sweden

In Sweden a cylindrical gap has been used. The diameter of the inner cylinder is about 150 mm. and the spacing or oil gap between the cylinders is 3 mm. The B.D.V. is divided by 0·3 in order to give the electric strength in kV/cm.

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